PRICE TEN SHILLINGS AND SIXPENCE

THE JOURNAL OF
The Institution of Electrical Engineers

ORIGINALLY

The Society of Telegraph Engineers

FOUNDED 1871

INCORPORATED BY ROYAL CHARTER 1921

EDITED BY P. F. ROWELL, SECRETARY

SAVOY PLACE, VICTORIA EMBANKMENT, LONDON, W.C.2

Telegrams: "VOLTAMPERE, PHONE, LONDON." Telephone: TEMPLE BAR 7676.

Vol. 83 AUGUST, 1938 No. 500

CONTENTS.

(*The Institution is not, as a body, responsible for the opinions expressed by individual authors or speakers.*)

E. and F. N. SPON LIMITED, 57 HAYMARKET, LONDON, S.W.1.
CHEMICAL PUBLISHING COMPANY OF N.Y. INC., 148 LAFAYETTE STREET, NEW YORK.

The Institution of Electrical Engineers.

FOUNDED 1871

INCORPORATED BY ROYAL CHARTER 1921

PATRON: HIS MAJESTY KING GEORGE VI.

COUNCIL, 1937–1938.

President.

SIR GEORGE LEE, O.B.E., M.C.

Past-Presidents.

COLONEL R. E. CROMPTON, C.B., F.R.S.
SIR JAMES SWINBURNE, BART., F.R.S.
CHARLES P. SPARKS, C.B.E.
ROGER T. SMITH.
LL. B. ATKINSON.
J. S. HIGHFIELD.
F. GILL, O.B.E.
A. RUSSELL, M.A., D.Sc., LL.D., F.R.S.
W. B. WOODHOUSE.
W. H. ECCLES, D.Sc., F.R.S.
SIR ARCHIBALD PAGE.
LIEUT.-COL. K. EDGCUMBE, T.D.
COLONEL SIR THOMAS F. PURVES, O.B.E.
CLIFFORD C. PATERSON, O.B.E., D.Sc.
J. M. DONALDSON, M.C.
PROF. E. W. MARCHANT, D.Sc.
P. V. HUNTER, C.B.E.
PROF. W. M. THORNTON, O.B.E., D.Sc., D.Eng.
J. M. KENNEDY, O.B.E.
H. T. YOUNG.

Vice-Presidents.

SIR NOEL ASHBRIDGE, B.Sc. (Eng.).
J. R. BEARD, M.Sc.
A. P. M. FLEMING, C.B.E., D.Eng., M.Sc.
JOHNSTONE WRIGHT.

Honorary Treasurer.

W. MCCLELLAND, C.B., O.B.E.

Ordinary Members of Council.

T. E. ALLIBONE, D.Sc., Ph.D.
COL. A. S. ANGWIN, D.S.O., M.C.
E. S. BYNG.
T. CARTER.
C. E. FAIRBURN, M.A.
F. FORREST.
PROF. C. L. FORTESCUE, O.B.E., M.A.
P. GOOD.
E. M. LEE, B.Sc.
E. LEETE.

Ordinary Members of Council—(*Continued*).

S. W. MELSOM.
F. E. J. OCKENDEN.
P. L. RIVIÈRE.
P. J. ROBINSON, M.Eng.
C. RODGERS, O.B.E., B.Sc., B.Eng.
C. D. TAITE.
C. R. WESTLAKE.
G. A. WHIPPLE, M.A.

Chairmen and Past-Chairmen of Local Centres.

Argentine Centre:
C. G. BARKER.
*H. C. SIDDELEY.

China Centre:
S. FLEMONS.
*C. R. WEBB.

Irish Centre:
LT.-COL. K. E. EDGEWORTH, D.S.O., M.C.
*W. STOREY.

Mersey and North Wales (Liverpool) Centre:
G. K. PATON.
*F. E. SPENCER.

North-Eastern Centre:
W. D. HORSLEY.
*D. M. BUIST.

North Midland Centre:
J. G. CRAVEN.
*S. R. SIVIOUR.

North-Western Centre:
J. W. THOMAS, LL.B., B.Sc.Tech.
*G. L. PORTER.

Scottish Centre:
MAJOR H. BELL, O.B.E., T.D.
*H. C. BABB.

South Midland Centre:
H. HOOPER.
*E. A. REYNOLDS, M.A.

Western Centre:
H. G. WEAVER.
*J. W. SPARK.

* Past-Chairman.

Chairmen of Sections.

H. COBDEN TURNER (*Meter and Instrument*).
J. L. EVE (*Transmission*).
T. WADSWORTH, M.Sc. (*Wireless*).

Secretary.

P. F. ROWELL.

Assistant Secretaries.

F. W. HEWITT, M.Sc.; A. E. RAYNER.

LOCAL CENTRES AND SUB-CENTRES.

ARGENTINE CENTRE.

Chairman.—C. G. BARKER.
Hon. Secretary.—R. G. PARROTT, Tucuman 117, Buenos Aires.

CHINA CENTRE.

Chairman.—S. FLEMONS.
Hon. Secretary.—W. MILES, c/o Shanghai Telephone Co., P.O. Box 1193, Shanghai, via Siberia.

IRISH CENTRE.

Chairman.—LT.-COL. K. E. EDGEWORTH, D.S.O., M.C.
Hon. Secretary.—R. N. EATON, 1, Foster Place, College Green, Dublin.

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE.

Chairman.—G. K. PATON.
Hon. Secretary.—W. PARRY, M.Eng., "Scaur," Birkenhead Road, Gt. Meols, Hoylake, Wirral, Cheshire.

NORTH-EASTERN CENTRE.

Chairman.—W. D. HORSLEY.
Hon. Secretary.—H. B. POYNDER, "Eastnor," Jesmond Park, Newcastle-on-Tyne, 6.

Tees-Side Sub-Centre.

Chairman.—J. H. HAWS.
Hon. Secretary.—H. SHAW, "Glenholme," Boosbeck, Saltburn, Yorks.

NORTH MIDLAND CENTRE.

Chairman.—J. G. CRAVEN.
Hon. Secretary.—W. R. T. SKINNER, B.Sc.(Eng.), 36, Park Place, Leeds, 1.

Sheffield Sub-Centre.

Chairman.—W. F. C. COOPER.
Hon. Secretary.—A. C. BOSTEL, 23, "Stumperlowe," Stumperlowe Lane, Sheffield 10.

[*Continued on page (III) of Cover.*

THE ELECTRICAL IGNITION OF MIXTURES OF ETHER VAPOUR, AIR, AND OXYGEN

By Professor W. M. THORNTON, O.B.E., D.Sc., D.Eng., Past-President.

(*Paper first received* 13*th February, and in final form* 19*th April*, 1937; *read before* THE INSTITUTION 24*th February, and before the* SCOTTISH CENTRE 8*th March*, 1938.)

SUMMARY

Explosions of ether-air or ether-oxygen mixtures have occurred from time to time in operating theatres, some of them with fatal results. Those having an electrical origin might often have been prevented had the conditions of electrical ignition of such mixtures been known. The proportions of ether and oxygen and air within which ignition is possible vary with the type of source. With hot wires, such as cauteries, ignition can occur within limits as wide as 3 to 80 per cent of ether in oxygen. With sparks, in general the limits are much narrower. The work described determines these limits and the least currents that cause ignition when broken slowly or suddenly, or by fusing wires. Second only to hot wires as a possible risk are the fizzling sparks at a slower intermittent break of circuit between fine wires. When the current is kept below certain well-defined values it is found that ignition can always be prevented. It is then only necessary to specify that the total resistance of the circuit for any given voltage shall be such that these currents cannot under any circumstances flow in the circuit. A factor of safety of 2 is ample for this purpose.

TABLE OF CONTENTS

(1) INTRODUCTION

For general anaesthesia, ether is in many cases preferable to chloroform; but they have this important difference, that while the latter cannot be ignited the former is highly inflammable. For most of the purposes for which they are required inflammability is not of the first importance, but for certain operations on the mouth and throat, in which electric lamps and cauteries are used, experience has shown that there are risks of ignition of the anaesthetic mixture, and there have recently been more fatal accidents from this cause. Ignitions by sparks of electrostatic origin, commonly known as static sparks, and by the hot wires of cauteries, or again by hot points due to bad contacts in the examining-lamp connections, or where the wires have been broken, are all possible. The electrical faults can be avoided by suitable design and construction of the fine leads that are used, and of their connections. Static sparks are almost impossible within the mouth or throat, where the moisture of respiration prevents any local concentration of surface charge and of rise of potential. Sparks due to the sudden complete interruption of the lamp or cautery circuit are equally rare; but a cautery is a possible source of ignition that requires close examination. The experiments to be described show that it is doubtful whether a cautery should ever be used with ether-oxygen mixtures, except under very carefully-guarded conditions of current and temperature. Cauteries should, in fact, only be used for throat operations, at the temperatures that are necessary, with an anaesthetic that gives the desired degree of insensibility and is much less inflammable than ether-oxygen.

(2) TYPES OF ELECTRICAL IGNITION

In any inflammable gaseous mixture there are very clearly-defined limits both of the proportions of the gas in air or oxygen that are explosive, and of the critical intensities of the source of ignition, whatever that may be.* The chemical limits of inflammability are not the same for different types of ignition. A static discharge spark, that is an electron jet, lasts only for a millionth of a second and is over before the molecules between which it passes have time to move. In electron discharge of this type, at relatively high potentials and at atmospheric pressure, it is usual to consider the gaseous molecules as at rest during the passage of the spark, so that any consequent chemical combination is the result of the electrical activation of the molecules by the impact of the electron stream upon them. Time therefore plays an important part in ignition by static or jump sparks; and the electrical conditions of voltage and current under which ignition occurs, or fails to occur, are very sharply critical. The probability of ignition depends not only on the intensity of the spark but on the rapidity of chemical combination in the mixture. The latter again depends on the proportions of the inflammable gas, and greatly on whether the mixture is made with oxygen or with air. The chemical or relative volume limits of inflammability are much wider when oxygen is used. Many types of ignition have been studied; for instance, by a single non-oscillatory impulse,† by a magneto spark that is intermittent or oscillatory,‡ by the interruption of a current-carrying circuit, with both direct and alternating current of low frequency,§ by high-frequency discharge,|| by hot wires,¶ by the spark when a current-carrying wire

* See Reference (1). † *Ibid.*, (2). ‡ *Ibid.*, (3).
§ *Ibid.*, (4). || *Ibid.*, (5). ¶ *Ibid.*, (6).

is drawn out and broken under tension,* by condenser discharge,† and more recently by corona discharge without sparks.‡

Part of this work has been done in order to find the conditions for unfailing ignition in internal-combustion engines, the rest to find those that with equal certainty prevent it, as in coal-mining or industrial processes. To the latter must now be added the risk in surgical operations or examinations.

(3) IGNITION OF ETHER-AIR AND ETHER-OXYGEN MIXTURES BY COIL SPARKS

Since a sustained stream of sparks could without doubt ignite any inflammable mixture, only the limits of inflammability were in this case to be determined, and further, in all the present work no attempt has been made to measure the rise of pressure of explosion or its rate of rise. The explosions of ether mixtures were sufficiently violent to shatter the glass window (¼ in. thick, 1½ in. diameter) of the explosion chamber. Ethylene-air mixtures are still more violent; and even when the space is not enclosed, so that the rise of pressure is negligible, the burning of these rapidly-combining gases, although transient, may be very severe.

The arrangement of the brass explosion chamber is shown in Fig. 1. The vessel containing ether was immersed in water that could be maintained at any desired temperature, to give a vapour pressure approaching atmospheric. Electrically-heated tubes led to the explosion chamber, which was itself surrounded by an electric heating coil, and similarly heated connections led to the mercury-column manometer. The thermal state of the whole was such that no condensation could take place in the tubes or explosion chamber or on the sparking contacts, the latter an important point to observe. The mixtures were all made by change of pressure. The height of the barometer having been read and the vessels exhausted, air or oxygen was admitted to an amount measured by the fall of vacuum. Ether vapour was then admitted to give the desired percentage, and finally air or oxygen until there was atmospheric pressure in the explosion chamber. The relative volumes were calculated from the pressure-changes. Ignition was made by a standard sparking-plug with the points 0·4 mm. apart, connected to a motor-car ignition coil giving a steady stream of sparks so long as the primary circuit was closed.

The front end of the explosion vessel was fitted with a thick glass window through which the passage of the spark and its effects could be observed. The results were as follows: The lower limit of *ether-air mixtures* was found to be at 3·14 per cent; the upper limit, beyond which ignition did not occur, was at 9·5 per cent. With *ether-oxygen mixtures* the observed limits were 2·98 and 45·5 per cent of ether vapour. In the former case the ratio of the upper to the lower limit is 3·02, which may be compared with the value of 3·37 obtained for the paraffins and a mean of 3·03 for a number of unsaturated hydrocarbons.* Since the proportion of oxygen in air is only 21 per cent, it was to be expected that with oxygen alone the limits of inflammability would be wider in proportion. The ratio 9·5/45·5 is 0·21, and the two sets of observations therefore agree.

In practice it is usual to blow a mixture of approximately 1 part of ether to 4 parts of oxygen towards the patient's mouth, and there is then some admixture of air. This does not affect the lower limit, where oxygen is always in excess. The upper limit is changed in proportion to the air admitted. Thus if there is air alone the upper limit is 9·5, with oxygen 45·5, and with half air and half oxygen it is nearly 27 per cent, the mean of these.

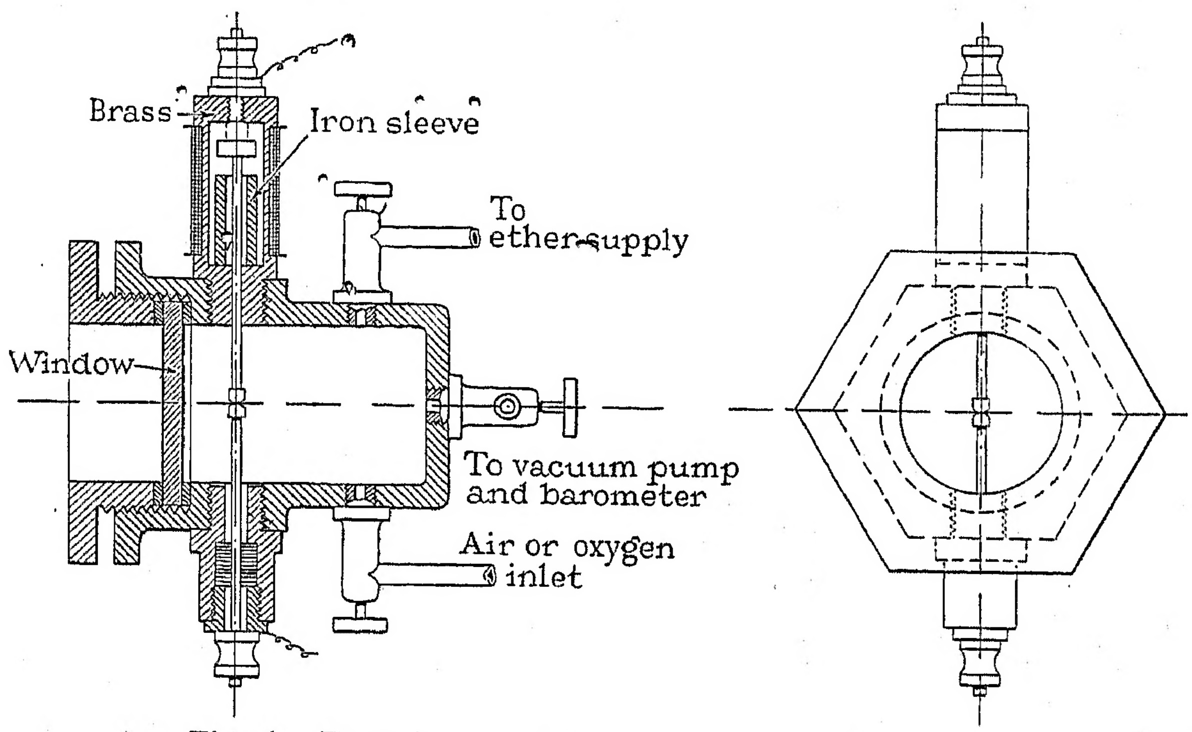


Fig. 1.—Explosion vessel arranged for circuit-break sparks.

(4) IGNITION BY CIRCUIT-BREAK SPARKS

A circuit-break spark is a miniature arc. The voltage between the contacts as they open is the product of the current and the resistance of the arc at any instant. It is therefore small when the contacts just open, and rises to the circuit voltage at the moment the arc is ex-

* See Reference (7). † *Ibid.*, (8). ‡ *Ibid.*, (9).

* See Reference (10).

tinguished. If the rate of separation of the contacts is small, as it is in any simple electromagnetic device having inertia, the spark has at first the characteristics of a maintained arc, and ignition is caused by contact of the inflammable mixture with the surface of the arc. The velocity of the electron stream that forms the arc may be great, but there is always interpenetration between it and the gaseous molecules, and it is on this that activation and ignition chiefly depend. The duration of the arc depends greatly on the inductance of the circuit. In a circuit consisting of secondary cells and resistances, an inductance of a millihenry, such as that of a resistance wound with a few turns per centimetre on a split steel tube, a common laboratory appliance, was sufficient in the case of ether-oxygen mixtures to lower the least igniting current to one-tenth of the value when non-inductive resistances were used. In order to bring out the special features of break-spark ignition uncomplicated by the effect of inductance (which could not be fully examined without an extended research with a cathode-ray oscillograph and high-speed camera, and is not important in surgical appliances), resistances wound anti-inductively were used and the circuit broken by a "knock-off" electromagnetic device in which relatively heavy moving parts were made to acquire a definite velocity before striking a free contact piece (to which the current was led by a flexible wire, shown dotted in Fig. 1) and so separating the poles. Nearly all the special character of break-spark ignition is disguised when the poles are made to open slowly, or when on the other hand a scraping contact is used by wiping a strip of spring metal past a fixed electrode. The results are given in Fig. 2. Using the most inflammable 6 per cent ether-air mixture and varying the circuit voltage, it is found that the product of this voltage and the least igniting current is hyperbolic in type. The curve of Fig. 2 fits closely the equation $I(V - 19) = 45$. Ignition of the most inflammable ether-air mixture by circuit-break sparks was therefore impossible below 19 volts, under the conditions of the experiment. The product VI is not the activity of the spark. When the gap opens, the current has its maximum value I, but the voltage is zero. At the moment of extinction I is zero and V is the circuit voltage. At some point in the length of the spark the product is a maximum, less than VI. A break spark or arc of this kind is not "explosive": it does not depend initially upon ionization by collision. At the moment of separation of the poles the electrons of the current leave the anode gently, since the temperature of the metal is low and the field across the gap is not high; and if the gap is kept short, so that the resistance of the arc compared with the rest of the circuit is small, the field is low and the ions are not accelerated to the same degree as when the gap has a larger fraction of the circuit voltage. The spark of a direct-current break in a circuit with no capacitance or inductance is a unidirectional stream impinging upon the cathode at a rate proportional to the product VI. If the metal of the poles is highly conducting, and their mass is so large that the incident energy is insufficient to raise the surface temperature to the point of emission of thermions, ignition does not in general follow. It is known that the metal of the poles has considerable influence on this kind of ignition, though not on jump-spark ignition.* It is only the radiation from the cathode, either thermionic or photo-electric, that is proportional to VI, the product of the circuit voltage and current, and the remarkably close fit between the calculated and observed values in Fig. 2 indicates that it is rigorously proportional, and also independent of the length of the spark, so far as this depends upon the circuit voltage.

Keeping the voltage constant at 50 volts, the highest ever likely to be used on surgical apparatus and much in excess of that advisable, the same type of curve (Fig. 3) of least igniting current is found for ether-air mixtures as in the ignition of the paraffins by direct-current break

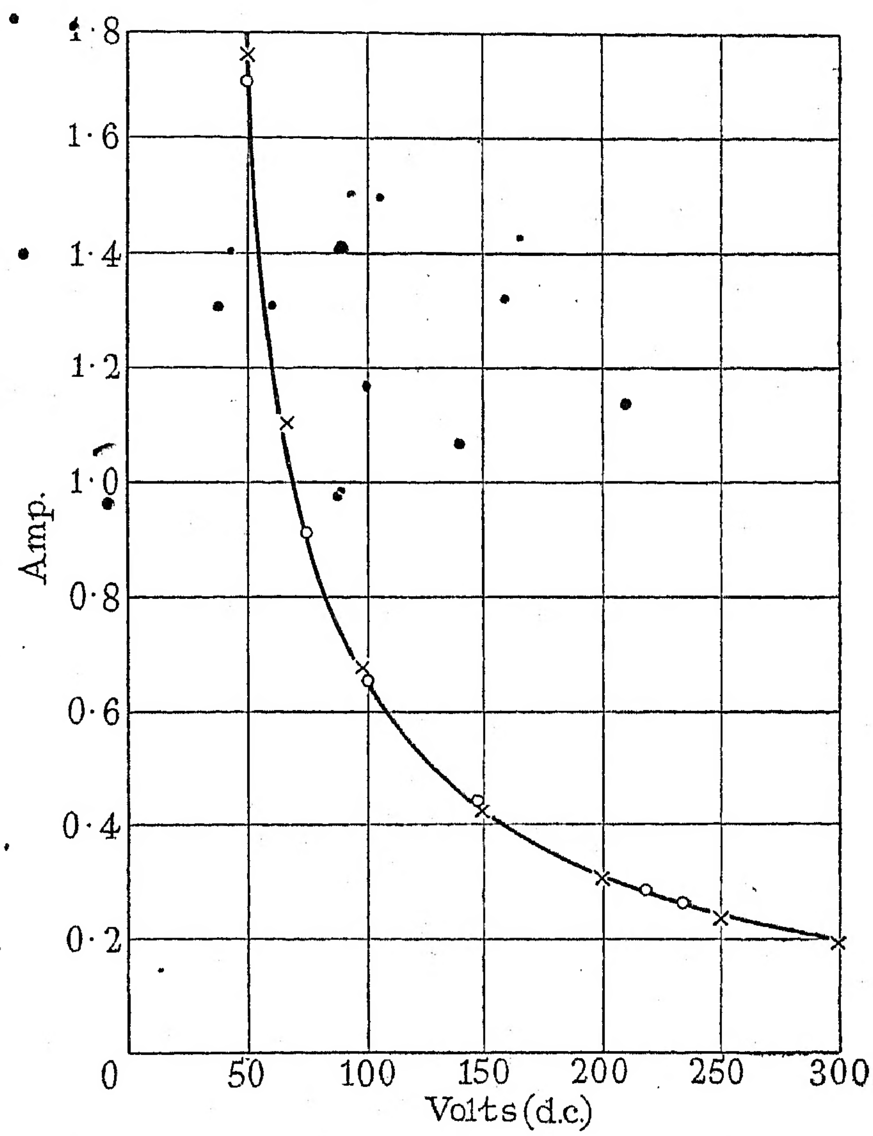


Fig. 2.—Ignition by break sparks: 6 per cent ether in air.

sparks.† The curve is the upper boundary of an area within which no ignition can occur, but which has two distinct phases. In the lower part from 3 to 6 per cent the product Ip is constant and equal in this case to $9 \cdot 0$, I being the least igniting current and p the percentage of ether in air. The portion from 6 per cent to the upper limit is a straight line in which I is directly proportional to p, and here $I = 0 \cdot 265p$. In the lower percentages, ignition depends almost entirely on the activation of the oxygen molecules, and to activate them so that in unit volume enough oxygen ions are produced to combine completely with the molecules of gas present requires an increase of current in inverse proportion to the pressure. At the upper limit there is a deficiency of oxygen, and

* See Reference (11).

† *Ibid.*, (12).

the current has again to be increased until the number of oxygen molecules which can be reached and activated and can combine with the gas are sufficient for the flame to spread. At both the upper and lower limits of inflammability the flame passes slowly through the mixture and there is little rise of pressure. In the phase when Ip is constant the product of the number of electrons passing through the mixture per second and the number of molecules of the inflammable gas present in unit volume is constant. There is excess of oxygen, and thus an increase of current is required in order to activate more than the minimum number necessary for ignition so that enough may reach the combustible molecules at a rate sufficient for inflammation to spread. Over the greater part of its length the curve of Fig. 3 follows

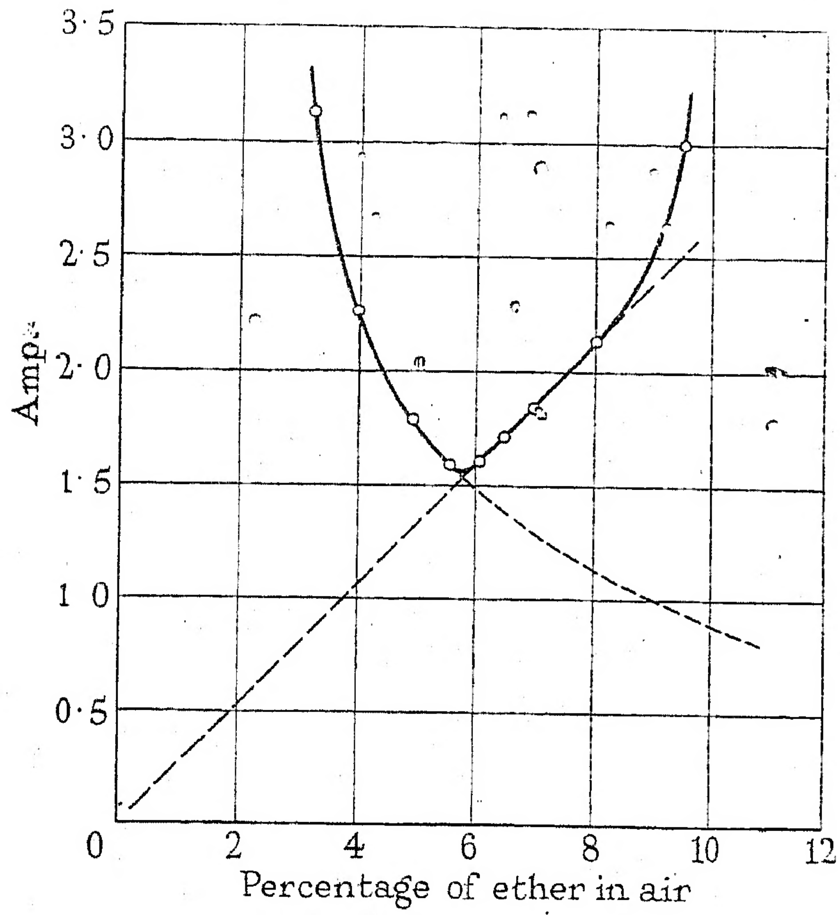


Fig. 3.—50-volt d.c. break sparks.

the equation $I = (a + bp^2)/p$. When p is small and p^2 negligible, Ip is equal to a and is constant. When p is large, $I = bp$, and there is a minimum when $I = \sqrt{(a/b)}$. The reasons for the shapes of these curves have been given elsewhere.*

The ignition of ether-oxygen mixtures differs from this in two particulars; there is in Fig. 4 a horizontal phase and towards the upper limit the curve is displaced to the right, so that the slope of the base passes not through zero but through the point of combustion to carbon dioxide, at 14·3 per cent of ether in oxygen. The type of spark remained the same throughout. Platinum rods with slightly rounded ends were used for poles, and were quite unaffected by these sparks whatever their intensity. The three phases are (i) Ip constant, (ii) I constant, and (iii) $I/(p - p_0)$ constant. These indicate differences in the rate of combination, or activation prior to combination. The first and last have been considered in reference to Fig. 3. The intermediate stage when I is constant is unusual in break-spark ignition, though common in ignition by condenser discharge sparks.* In the latter case it always indicates an interval between two critical mixtures in which the number of oxygen atoms taking

* See Reference (1).

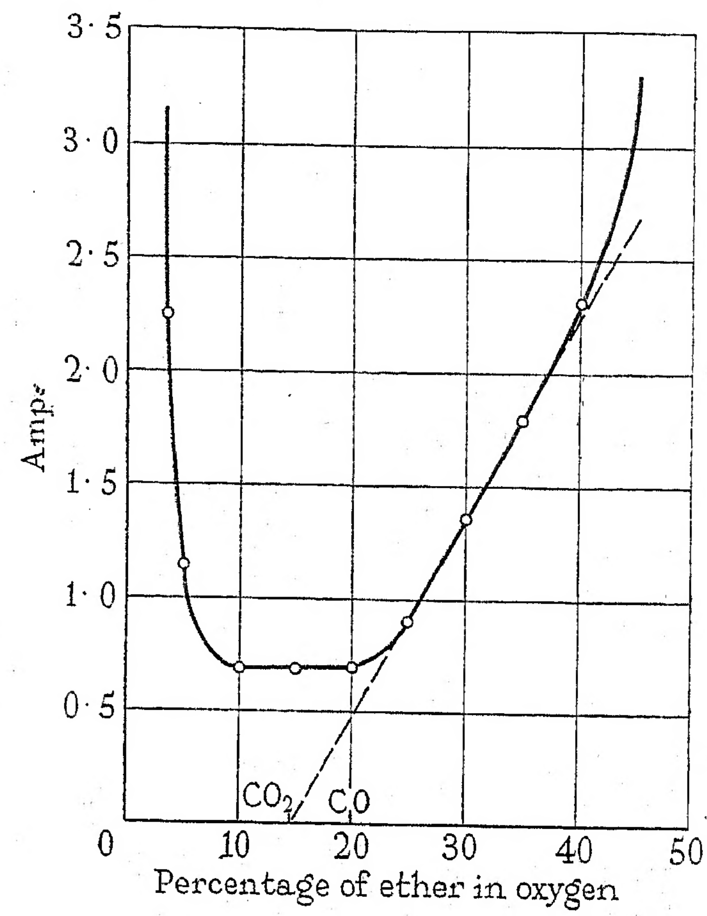


Fig. 4.—50-volt d.c. break sparks.

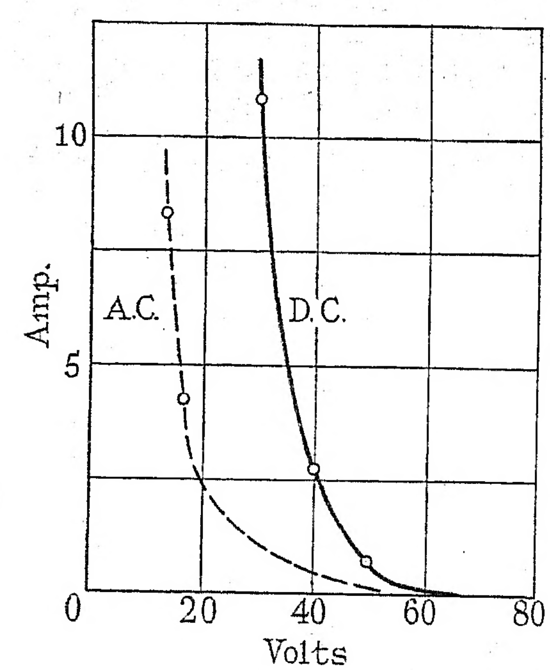


Fig. 5.—Ignition by break sparks: 14 per cent ether in oxygen.

part in the reaction changes by an integral number. In Fig. 4 the flat base lies between the points of combustion to CO_2 and to CO, the first requiring 12 molecules of O_2, the second 9. Between these proportions of oxygen to one molecule of ether the electrical stimulus required for

* See Reference (8).

ignition remains the same; it is the oxygen only that matters.

From what has been said about the influence of small inductances in the circuit it can be inferred that ether mixtures are unusually sensitive to the rise of voltage at break of circuit.* Ether apparently has a low ionizing potential. It is well known that there is for all metals a minimum arcing voltage below which a steady arc cannot be maintained. The influence of this on ignition is shown, in the present case, by the marked effect of lowering the circuit voltage. Keeping the mixture constant at 14 per cent of ether, the least direct current that caused ignition at 50 volts was 0·65 amp.; at 40 volts this rose to 2·75 amp., and at 30 volts ignition could only be obtained by currents well above 10 amp. (Fig. 5). The advantage of using low-voltage apparatus, from this point of view, can scarcely be exaggerated, though clean breaks are not likely to be a source of ignition in medical apparatus. The work was done to examine this type of ignition of ether mixtures under perfectly-controlled and regular conditions.

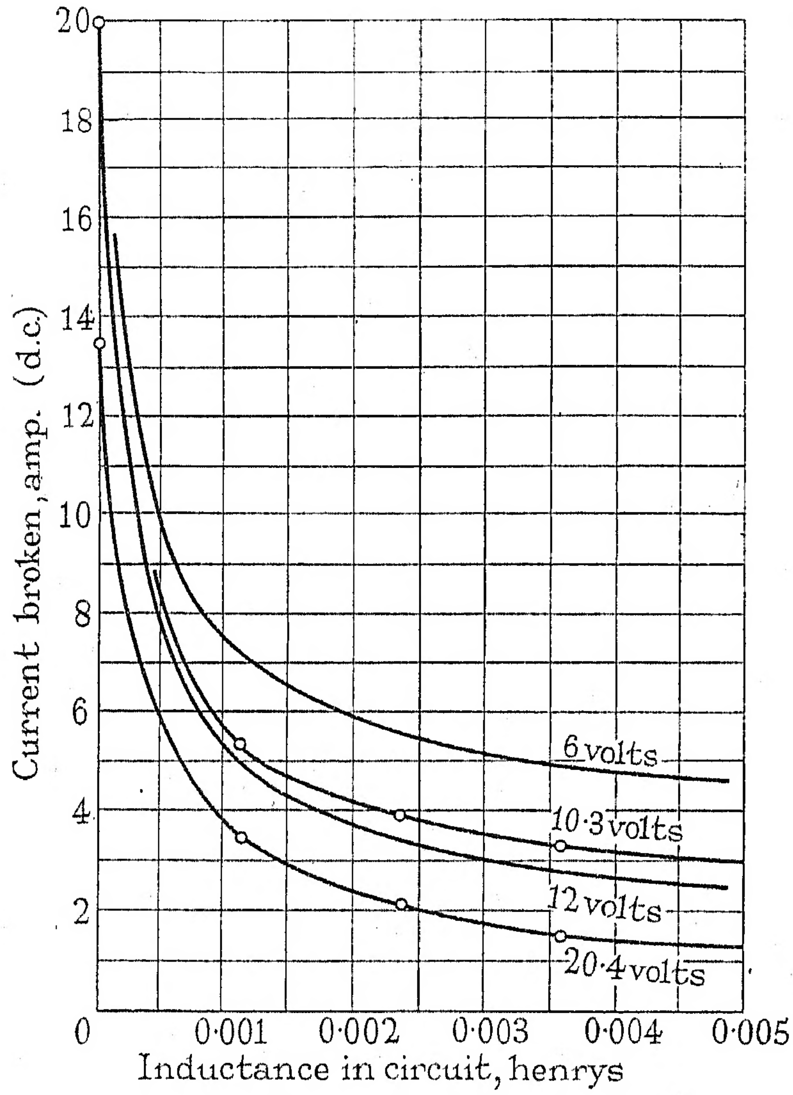


Fig. 6.—Influence of inductance on ignition of ether-oxygen mixture containing 14·3 per cent ether.

(5) INFLUENCE OF INDUCTANCE

(a) Direct-current Circuits

In order to observe more fully the influence of inductance on ignition, four coils were wound, on split brass tubes, each having an inductance of 0·0012 henry and a resistance of 0·835 ohm. These were connected in series with a carbon rheostat through the magnetic break in the explosion chamber. The immediate object of this part of the work was to find the resistance which when connected in series with a given inductance would just prevent ignition. Fig. 6 gives the results of measurements with both voltage and inductance varied. From these curves the limiting resistances shown in Fig. 7 were calculated. The limiting resistance, when the current was as nearly as possible non-inductive, was also measured, and it is seen that the curves converge to a point to the left of zero. This is due to the residual inductance of the leads, resistances, and apparatus, that cannot be varied. The coincidence of the curves at this point shows clearly that, if the circuit could be made entirely non-inductive, ignition would not be possible at any of the voltages examined, so long as the cells (which in this case were storage batteries) and the connections to them had no more than their inherent small resistance.

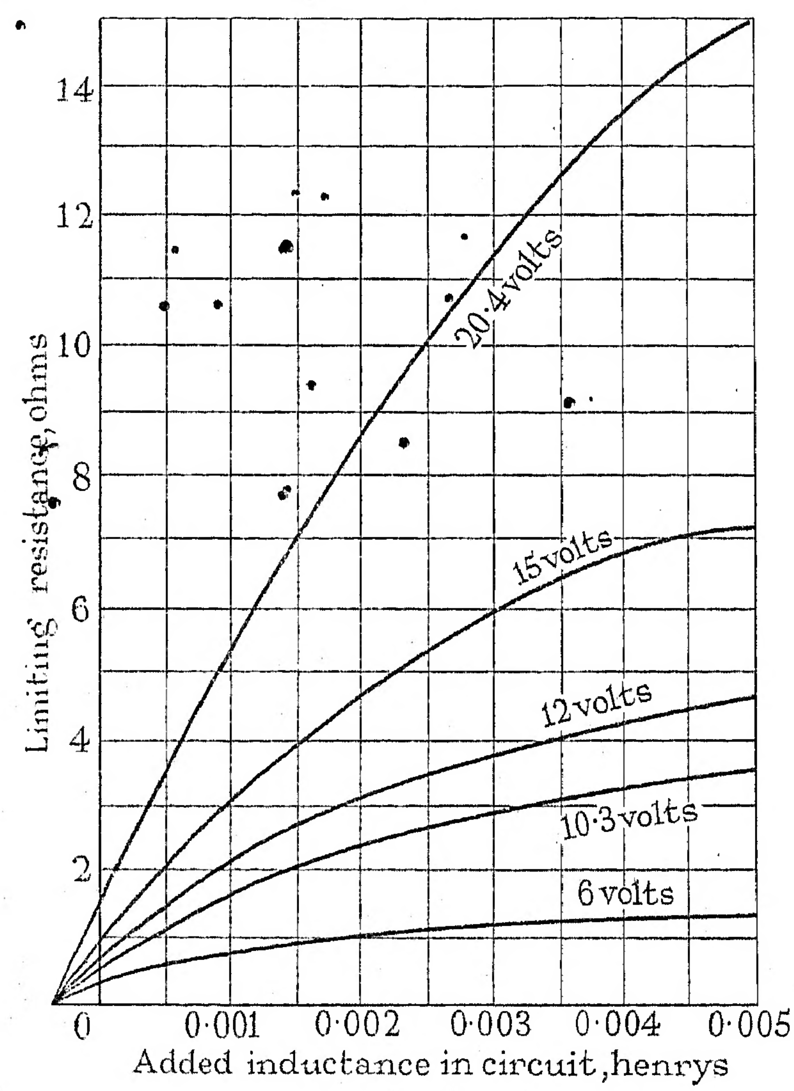


Fig. 7.—Least resistance to be inserted to prevent ignition of ether-oxygen mixture containing 14·3 per cent ether.

The influence of inductance is to intensify the spark at break by adding to the circuit voltage an inductive transient component which may be, as in electric bells, much greater than the battery voltage.* Ignition by break sparks depends more on the initial voltage-gradient in the break than on the energy of the spark. This transient voltage can be suppressed by connecting across the break either a resistance or a capacitance. If, there-

* See Reference (13).

* See Reference (14).

fore, there is any possibility of a break occurring in the wires of an electrical cautery or examining lamp, the risk can be lessened by placing a resistance of the same order as that of the lamp or cautery in parallel with it, so as to shunt the voltage-rise, or by using a condenser for the same purpose.

Safety is ensured by arranging the circuit so that the portion of the battery current (it may be even when it is short-circuited through the break) which passes through the opening contacts does not exceed that shown by the ordinates in Fig. 6 to be safe for the voltage used. The capacitance of the condenser, connected in parallel with the gap, which will do this depends upon the rate at which the break is made. The battery current is given by $i = E/r_0$. The part of this that passes to the condenser is $i_2 = Cdv/dt$, where V is the voltage across the break. That in the break is $i_1 = i - Cdv/dt$. It has been shown* that the voltage across the break in a non-inductive circuit is $V = Et/T$, where T is the total time of break. Thus $dv/dt = E/T$, and is constant while the gap is opening, so that $i_1 = i - C\frac{E}{T}$. The capacitance required to prevent the spark firing the gas is $C = (i - i_1)T/E$. When the break is slow it is necessary to use a large condenser to prevent ignition and, if it is made with very great rapidity, so small a condenser is necessary that the capacitance between the separating contacts may be sufficient to prevent it. Such a rapid break is unlikely to occur in practice, except perhaps where a heavy piece of apparatus falls and breaks a wire attached to it. In that case there is little probability of the presence of an explosive mixture.

The equations of the curves that are found to connect the total circuit inductance and the least igniting current of ether-air mixtures are, for two voltages,

$$L(i_0 - 0\cdot 60) = 0\cdot 004, \text{ at } 20\cdot 4 \text{ volts}$$

and

$$L(i_0 - 2\cdot 0) = 0\cdot 005, \text{ at } 10\cdot 3 \text{ volts}$$

The numbers on either side of the equations are only constant for their respective voltages. They are, however, regular functions of the voltage.

The physical significance of these results is, first, that there is a lower limit of current at and below which ignition does not occur, however great the inductance may be made, when the circuit is broken in the manner specified. An equally important feature is that ignition depends closely upon the product Li and not upon $\frac{1}{2}Li^2$, the heat energy of the spark. There are at the present time two theories of ignition: that in which the combination of the hitherto inert molecules of the combustible gas and air is considered to be started by their electrical activation, by collision of electrons with molecules in a strong electric field, or by intense radiation; and that in which the effect is regarded as thermal—a simple heat-exchange. The latter is the obvious first approximation, but it is unable to account for many of the phenomena of ignition observed by the author and by Finch, such as the differences between direct and high- and low-frequency alternating-current break sparks, the stepped ignition obtained in particular with condenser discharge sparks, and the remarkable results obtained in ignition by hot wires. Finch has shown that on thermodynamic grounds the thermal theory is untenable. The present results support the electric theory in that they show ignition to be proportional to the electric field across the gap and not to the heat of the spark. In any inductive circuit $e = d\Phi/dt$, where Φ is the linked magnetic flux, and $d\Phi = Ldi$, or $Ldi = edt$; so that a term of the form Li is the product of a voltage and a time. In this case the voltage is that added by inductance. The influence of inductance is to maintain the voltage gradient in the gap at break at a higher value than it would have if the circuit were non-inductive, and therefore to increase the probability of ionization by collision with the molecules of the explosive mixture penetrating the spark. The complete theory of ignition would take account of the circuit voltage, the influence of which is to modify the numerical terms in the equations. The higher this voltage the lower is the value of the current to which the curves are asymptotic.

* See Reference (15).

(b) Alternating-current Circuits

For electromedical apparatus of the kind under consideration alternating current is often used, transformed down to voltages not exceeding 20 volts. A small transformer, connected to a 240-volt 40-cycle supply, had two low-voltage tappings. That giving 13·5 volts had a resistance of 0·059 ohm and a leakage inductance of 3·2 microhenrys; the other, giving 17·5 volts, had 0·145 ohm and 27·4 microhenrys. When these were used as a source the least igniting currents for the same break as before were 8·4 and 4·5 amperes respectively. These points are marked in Fig. 5 and show that the small inherent inductances in alternating-current circuits may make them ignite ether mixtures more readily than non-inductive direct-current circuits, a result of practical interest in electromedical technique.

The rise of voltage due to inductance in a given circuit is greater in proportion to the applied voltage when the latter is small, and it is therefore of the first importance to keep all low-voltage circuits as nearly as possible non-inductive and to use resistances designed for this purpose.

(6) IGNITION BY SINGLE JUMP SPARKS

It is possible to have jump sparks 1 cm. long passed through a highly inflammable mixture without firing it, from coils having high-resistance windings; and short sparks between massive electrodes do not allow free access of the gas to the spark. Sparks 1 mm. long are suitable for examining the igniting effect of single impulsive discharges, and in the present case the sparking points of a motor-car ignition plug were opened to this distance apart. The trembler contact of the coil was locked and the primary circuit made and broken by a single quick-action switch such as is used in the testing of capacitance. It was found that, when a current of 1·5 amperes was broken in the primary circuit, a spark just passed or failed to pass between the sparking points in the secondary circuit, in air at atmospheric pressure. In a 15 per cent mixture of ether and oxygen, ignition was obtained with every break above this value. It was too dangerous to attempt to observe the passage of this thin small spark through this ether-oxygen mixture by

approaching the eye close to the window, even with a glass shield, but it can be concluded that any jump spark of this length will ignite the very inflammable mixture used, and this probably holds for the static sparks observed when blankets are suddenly separated in very dry atmospheres. Any attempt to imitate the latter conditions is difficult, for ignition does not depend solely on the voltage or length of the spark, but to some extent, not at present known, on the intensity of single straight sparks. Since they are formed entirely by ionization by collision it is probable that ignition depends to some extent on the sectional area of the spark, i.e. on the concentration of the molecules of the mixture that are activated by its passage. The effect of this on ignition is a function of the voltage gradient, the current, the duration of the spark, the nature of the molecules of the inflammable gas, their proportion in air or oxygen, and the pressure. It may be remarked again that from earlier work on this subject it was concluded that ignition cannot be a simple thermal phenomenon, but that the start of the chemical combination that leads to an explosion is essentially electrical, an " activation " of the mixture.* The general question has been examined at length by Prof. G. I. Finch, who has shown conclusively that ignition requires the combining gases to be energized electrically,† and that it is not thermal in origin.

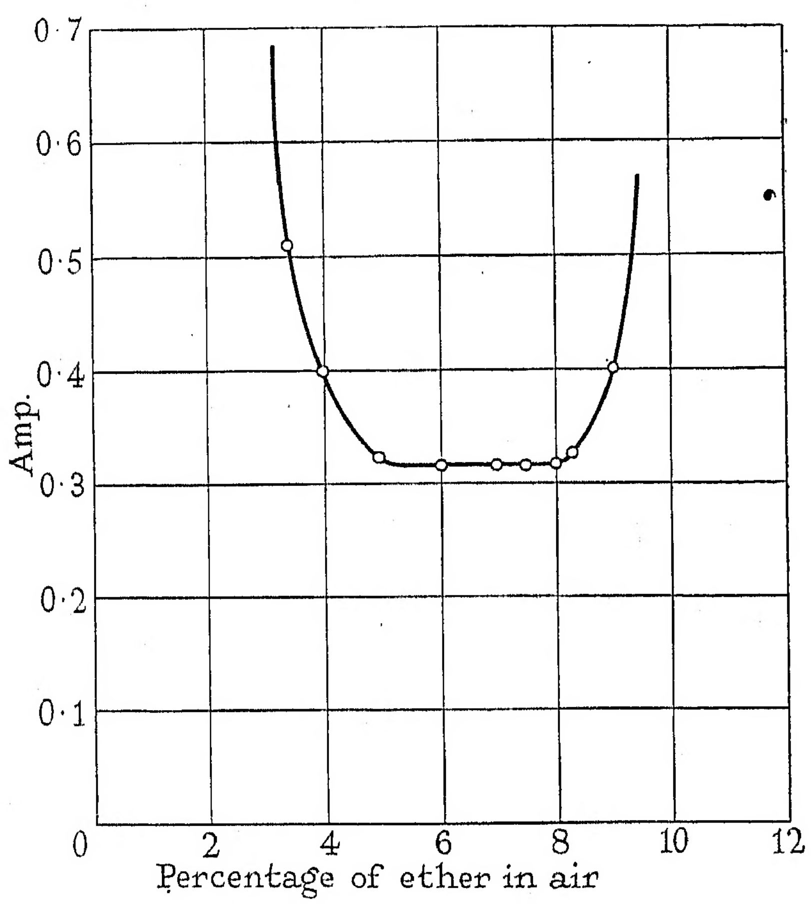


Fig. 8.—Ignition by hot wires.

(7) IGNITION BY HOT WIRES

The observations described in the previous sections define the limits of inflammability of ether-air and ether-oxygen mixtures under the specified conditions. Probably the most frequent cause of ignition of ether mixtures is the electric cautery. This is a necessary part of the surgeon's equipment for throat and nose operations. The temperature of the hot wire must be sufficient to disintegrate the organic tissues, and must therefore be above 250° C., approaching in some cases 500° C. To examine this form of ignition a wire of platinum with 10 per cent iridium was chosen, of which the characteristics were well known from researches on the ignition of methane. Its diameter was 0·07 mm., and to obtain a greater concentration of action it was wound in a spiral of 0·3 mm. inside diameter, to a length of 2 mm., having 15 turns in all. The tail ends of the spiral were soldered to two wires fixed into a sparking-plug fitting, in such a manner that the axis of the spiral was horizontal when in use. The position is important, for the rate of supply of gas to the spiral by convection is faster when the axis of the latter is vertical. There is in this case also a definite relation between the intensity and nature of the source of ignition and the limits of inflammability. The lower limit of ether-air mixture was found to be 3·14 per cent of ether, the upper limit about 9 per cent, above which ignition did not occur (Fig. 8). The method used was to start with a current a little below that found by

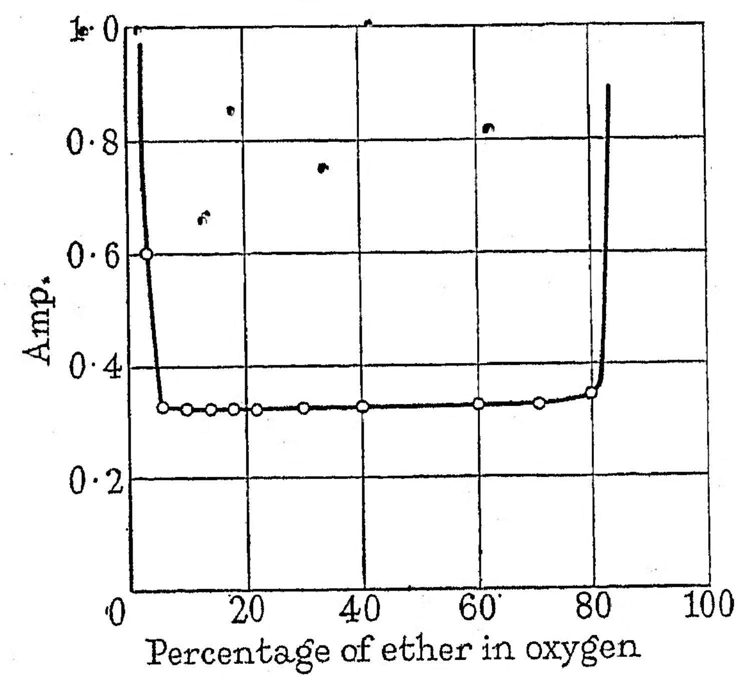


Fig. 9.—Ignition by hot wires.

trial to be the least igniting current in the spiral in the most sensitive mixtures, and to raise it at the rate of about 0·1 amp. a second until ignition occurred. At the limits the temperature of the wire was raised rather more rapidly and almost to fusing point. With ether-oxygen mixtures the results are shown in Fig. 9; the limits found were at 2·98 and about 80 per cent of ether. The lower limit is, as before, that at which there is not enough inflammable vapour in the element of volume of gas in contact with the source to cause it to burn quickly enough for the transmission of flame through the rest of the mixture, and the upper limit is where there is not enough oxygen activated to burn the gas quickly enough for a flame to spread. At the lower limit it is clearly the proportion of vapour and not of oxygen (which is in excess) that is important, for the lower limits with air and oxygen are so nearly alike. It is remarkable that the upper limit for oxygen is so much higher with hot wires than for streaming-spark ignition. It may depend on the relative rates of supply of gas to the spark or hot wire. This is

* See Reference (16). † *Ibid.*, (17).

certainly faster in the hot-wire case, for the convection stream is well established before the wire reaches ignition point.

Much the most conspicuous feature of ignition by hot wires is that, as with so many inflammable gases, the current required to start ignition does not depend upon the proportions of ether in the air or oxygen.* The same current, 0·32 amp., fired every mixture of ether and oxygen from 3·0 to 83 per cent of ether. This current was not sufficient to heat the wire to the point where it would glow or be visible in darkness, and the total power given to the wire was about 0·25 watt. The temperature was sufficient to burn the skin, and is therefore comparable with that associated with cautery conditions. It is to be noted that it is at temperatures from 300° C. that thermionic emission from a hot wire begins. The lower limits of vapour percentage were unaffected, and the upper limits were extended in proportion to the relative amount of oxygen present.

The conclusion to be drawn from these hot-wire results is that cauteries or any heated metals must be regarded as highly dangerous when in contact with either ether-oxygen or ether-air mixtures; that ether is, in fact, too inflammable to be used in any proportions where there are such possibilities of ignition. The temperature of an inspection flash-lamp bulb is far below danger limits. A local hot spot in the leads due to a broken wire, or a bad connection at the lamp terminals, might possibly be sufficient to ignite the gas if it reached the above temperature. Any operating-table apparatus in which such temperatures may be reached, whether induced by high-frequency oscillations or by open heating or sparking, is a potential source of danger.

It would appear that in almost all hot-wire ignition the first effect of the radiation from the wire is to activate molecules of the oxygen present, since this form of ignition is so largely independent of the proportion of inflammable vapour, and that the subsequent explosion is the attachment of these molecules to the hydrocarbon vapour and a "hydroxylation," in the manner shown by Prof. W. A. Bone to explain the combustion of other hydrocarbons.†

(8) IGNITION BY FUSED WIRES

The first observations were made on ether-air mixtures with 6 per cent of ether. Copper wire of No. 36 S.W.G., heated to bright redness, did not cause ignition. The wire was 3 cm. long, and vertical. When a 2-volt cell was connected to the wire as a short-circuit the mixture fired when the wire fused. A similar length of lead wire of the same diameter did not fire the mixture, even when short-circuiting 12 volts, but when the wire was doubled it did. Although a flash was visible at the moment of fusion in the mixture no ignition followed with single lead wires, but with tin wires of the same diameter ignition always followed the blowing of the fuse on short-circuit.

A single strand of No. 28 S.W.G. copper wire fired 15 per cent ether-oxygen mixtures every time with 12 volts in the circuit, and with a marked time-lag on 2 volts, taking then 3·5 amperes. Ignition in ether-oxygen mixtures always follows the fusion of a wire. It is the spark at the melting point that appears to be the cause of ignition, for before this a straight copper wire can glow red hot without firing the mixture. The exposure of a fresh metallic surface is known to be an active source of ionization or other activating radiation. Surfaces such as those of copper or lead wires that are quickly oxidized do not activate oxygen readily by electron emission.

With currents alternating at 50 cycles per sec., lead fuses cause ignition with as little as 2 volts in the circuit. There is some delay, but ignition follows certainly. It appears to be even easier with alternating than with direct currents at these low voltages. For the same ammeter reading the maximum field across the gap is 40 per cent higher when the current is alternating. There is little to be gained by using alternating-current apparatus for this purpose.

From former evidence, the same will apply to ignition when a current-carrying wire is broken in an inflammable mixture. The conditions at the breaking point are similar to those of a wire fused by the passage of a current.

These results of ignition by fused wires are given in order to show the kind of effect obtained. The combination is one of hot-wire and break-spark ignition and is complex in its action. It is just possible that a wire might be fused in this manner in an operating theatre in an inflammable mixture, but it should be highly improbable if the usual precautions are taken.

(9) IGNITION BY "FIZZLING" SPARKS

There are in use at the present time for throat inspection fittings of inferior design in which the supply, from cells or a transformer, is led to the lampholder by fine flexible wires. Breaks have been found in the union between the flexible and rigid parts of the apparatus, and there is grave risk of ignition at such a point unless the design is modified so that breaks cannot occur. It is, however, possible even in these most dangerous circumstances to raise the factor of safety from ignition so that the latter becomes highly improbable if not impossible. To do this it is first necessary to find, as before, the least igniting current and then to insert resistances in the circuit so that this current can never flow even when the leads are short-circuited.

In order to examine the conditions of ignition of ether-oxygen mixtures under these circumstances two series of measurements were made. The work that has been described in Sections (4) and (5) had clearly in view the fact that clean breaks were unlikely to occur in apparatus of the kind under consideration, but it was necessary to proceed in the first place as if they could so occur, in order to determine what might be called the most unfavourable limits of ignition, i.e. those in which ignition was most difficult.

(a) Measurements in Explosion Vessel

The first of the new series of measurements deals with breaks made with the same apparatus as before and in the same way, but with the contacts replaced by tufts or brushes of fine copper wire—pieces of "flexible" stripped of its insulation. When the contacts were closed these fine wires were interlaced and the electromagnet used to separate them was so adjusted that by closing and opening a tapping switch quickly a flickering or fizzling spark

* See Reference (16).

† *Ibid.*, (17).

could be made. This imitated, as well as could be done without hand operation, the kind of spark likely to be formed at the break of the last strands of a frayed wire. The resistances were wound anti-inductively and the same were used in both direct- and alternating-current measurements. The explosive mixture used was 14·5 per cent ether in oxygen by volume.

(i) Direct current.

The source of the current was a 12-volt car battery of negligible internal resistance. The results were as shown in Table 1; the least safe resistances are given in the last column.

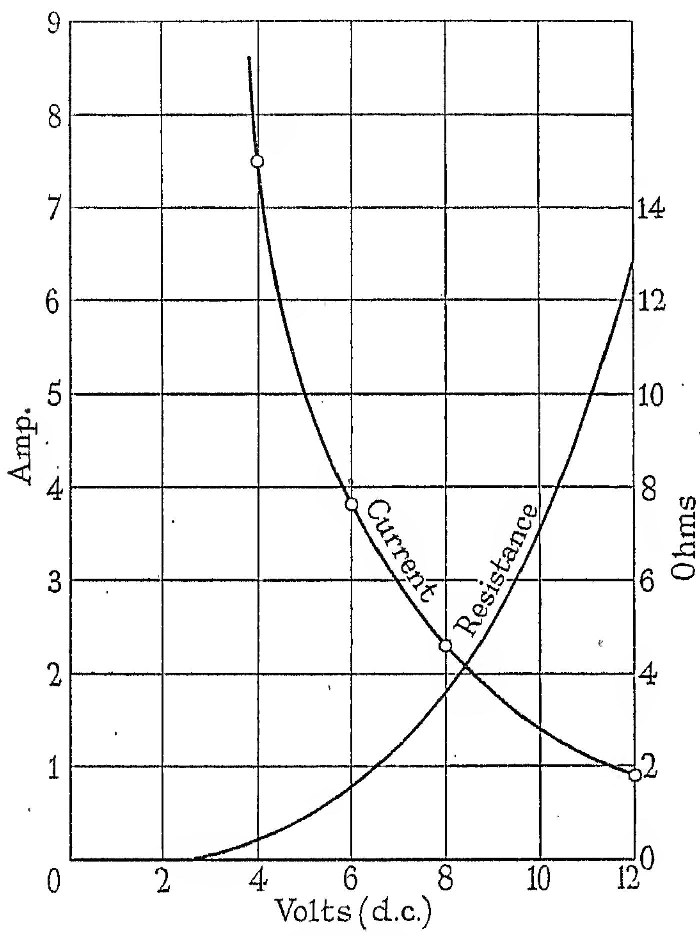


Fig. 10.—Limiting conditions for ignition by "fizzling" sparks in explosion vessel (Fig. 1), with direct current.

Fig. 10 shows that below about 3·0 volts ignition could not be obtained in this way. The curve is not truly hyperbolic, i.e. the product of current and voltage is not quite constant even when the vertical axis is taken at 3·0 volts. In order to give a factor of safety of 2 the resistance in col. 3 of Table 1 should be doubled. Lamps or apparatus in use would rarely or never take as much current as that quoted in col. 2. It is only in cases of a short-circuit in the lamp or its socket that the current could rise to danger values, and with a buffer resistance this could be prevented.

Table 1

Circuit voltage	Least igniting current	Limiting resistance
volts	amperes	ohms
4	7·5	0·53
6	3·8	1·58
8	2·3	3·48
12	0·9	13·3

(ii) Alternating current.

Ignition by alternating-current break sparks between fine wires—or by broken wires—is always easier than by direct current, probably in this case because of inductance, but the point requires further examination. In the present work the current was obtained from a transformer supplied at 250 volts, 40 cycles per sec., with separate multiple secondary windings. The circuit was in other respects the same as that employed with direct current. The results are given in Table 2 and Fig. 11.

With alternating current there is no lower limit of voltage at which the risk of ignition is negligible. Even at 2 volts ignition is possible. Reliance must in this case be placed entirely on the buffer resistance, and there is an ample margin of power for its use. The limiting resistances must have double the value for the same circuit voltage when alternating current is used instead of direct current.

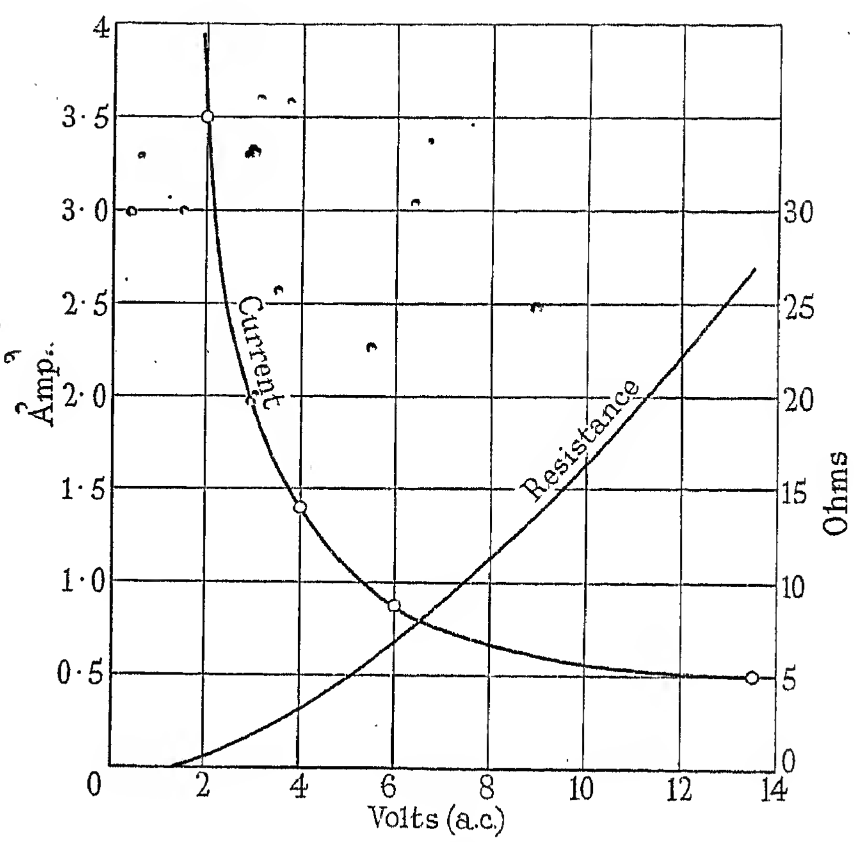


Fig. 11.—Limiting conditions for ignition by "fizzling" sparks in explosion vessel, with alternating current.

Table 2

Circuit voltage	Least igniting current	Limiting resistance
volts	amperes	ohms
2·0	3·50	0·57
4·0	1·40	2·85
6·0	0·88	6·82
13·5	0·50	27·0

In all of the above work the ignitions were made in the explosion vessel of Fig. 1 and were very violent. The brightness of the explosion was such that when seen

through the window, at a safe distance, the image persisted for a minute, as when one looks at the sun, though the explosion could not have lasted more than a thousandth of a second.

(b) Measurements on Open Sparks

The second series of measurements was made to find, if possible, how ignition occurred in a combined jet of ether and oxygen mixing in air and playing directly on brushes of copper wire stroked together by hand, causing streams of sparks between the fine wires. Such sparks last a short time but are frequently very bright. Behind the brushes was placed a curved metal screen like a reflector to facilitate the thorough mixing of the gases.

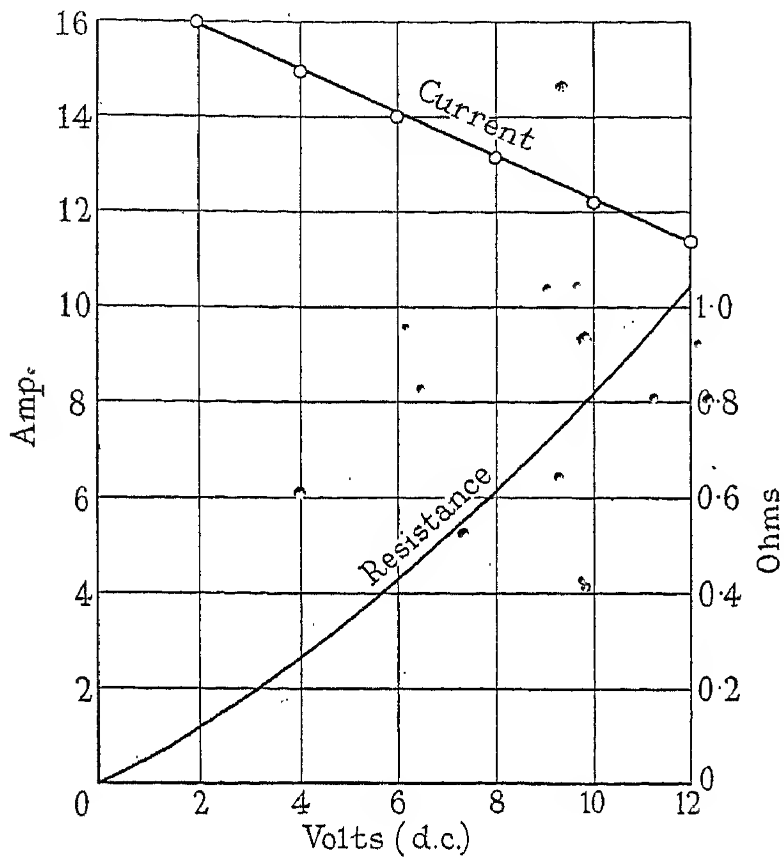


Fig. 12.—Least igniting current and lowest safe resistance for sparks between frayed ends of copper wire: open jets of ether-oxygen-air mixtures, direct current.

Table 3

Voltage	Least igniting current	Total resistance in circuit
volts	amperes	ohms
2	16	0·12
4	15	0·26
6	14	0·43
8	13·2	0·60
10	12·2	0·61
12	11·5	1·04

When ignition took place the flame of the burning jet had to be blown out, not always easily.

(i) Direct current.

The first set of observations on these open sparks was made using, as before, direct current from secondary cells, in the form of a 12-volt car battery. The currents below which no ignition occurred are given in Table 3 and Fig. 12.

When the resistance in each case was greater than the figure quoted in the last column of Table 3 no ignition occurred with the break made in the manner described. From the point of view of ignition there is nothing to be gained by lowering the voltage below 3 or 4 volts. At 10 volts the circuit power at the limit was 120 watts. From the point of view of power to be broken the higher voltages would have an advantage, if there were any real need to use them.

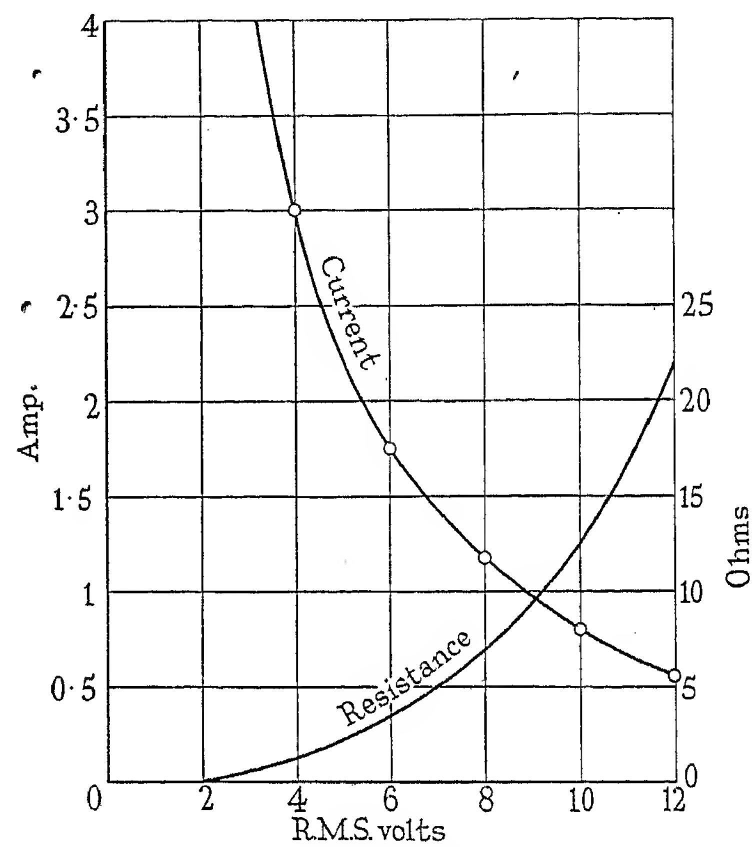


Fig. 13.—Results obtained under same conditions as in Fig. 12, but with alternating current.

(ii) Alternating current.

This was obtained from a 50-cycle generator with the field controlled to give 25 volts to a small transformer with 25 tappings. By the nature of the case the circuit was more inductive than when cells were used. The results obtained are given in Table 4 and Fig. 13.

Table 4

R.M.S. voltage (V)	Least igniting current (I)	Circuit resistance	Ratio, d.c./a.c.
volts	amperes	ohms	
2	over 4·6	0	∞
4	3·0	1·33	5·0
6	1·75	3·25	8·0
8	1·17	6·66	11·3
10	0·80	12·5	15·0
12	0·55	21·8	20·9

Ignition by alternating current is therefore much more sensitive to increase of voltage than is ignition by direct current. There is a real gain in using the lowest possible voltages, and the curve of Fig. 13 is nearly a rectangular hyperbola with a vertical axis at 2·0 volts. The equation

to the curve is $(V - 2)i \simeq 6 \cdot 5$. The power is now greatest at the lowest currents, and below 2 volts ignition was found to be impossible. A voltage not higher than 2 to 3 volts is indicated for inspection lamps when alternating current must necessarily be used.

The results of the work on ignition sparks between frayed-out wires may be summarized as follows: Gauged by the current that can be broken, direct current, even from secondary cells, is much safer than alternating current, though both can be made safe by appropriate buffer resistances. In view of these results it may be necessary to discourage the use of alternating currents for small inspection lamps (for cells are always available and convenient) and to require that the inherent or buffer resistances of the circuit and battery should be at least twice the limiting resistances found above.

The author is indebted to Mr. R. Bruce, M.Sc., for the skill and care with which he carried out much of the experimental work described.

REFERENCES

(1) W. M. THORNTON: "The Electrical Ignition of Gaseous Mixtures," *Proceedings of the Royal Society*, A, 1914, vol. 90, p. 281.

(2) W. M. THORNTON: "The Ignition of Gases by Impulsive Electrical Discharge," *ibid.*, 1916, vol. 92, p. 381.

(3) C. C. PATERSON and N. CAMPBELL: "Some Characteristics of the Spark Discharge and its Effect in Igniting Explosive Mixtures," *Proceedings of the Physical Society*, 1919, vol. 31, p. 168.

(4) See Figs. 2 and 12 of Reference (1).

(5) G. I. FINCH and H. H. THOMPSON: "The Effect of Frequency on the Condenser Discharge Ignition of Carbonic Oxide—Air Detonating Gas," *Proceedings of the Royal Society*, A, 1931–32, vol. 134, p. 343.

(6) W. M. THORNTON: "The Ignition of Gases by Hot Wires," *Philosophical Magazine*, 1919, vol. 38, p. 613.

(7) W. M. THORNTON: "The Ignition of Firedamp," *Colliery Engineering*, September 1926, p. 390.

(8) W. M. THORNTON: "The Ignition of Gases by Condenser Discharge Sparks," *Proceedings of the Royal Society*, A, 1914, vol. 91, p. 17.

(9) TCHANG TE LOU: *Science Abstracts*, B, 1933, vol. 36, Abs. No. 2332, and 1934, vol. 37, Abs. No. 792; also R. W. SLOANE: "The Ignition of Gaseous Mixtures by the Corona Discharge," *Philosophical Magazine*, 1935, vol. 19, p. 998.

(10) W. M. THORNTON: "The Limits of Inflammability of Gaseous Mixtures," *Philosophical Magazine*, 1917, vol. 33, p. 195.

(11) W. M. THORNTON: "The Reaction between Gas and Pole in the Electrical Ignition of Gaseous Mixtures," *Proceedings of the Royal Society*, A, 1915, vol. 92, p. 9.

(12) See Figs. 2, 3, 5, 8, and 12 of Reference (1).

(13) W. M. THORNTON: "The Ignition of Coal Gas and Methane by Momentary Electric Arcs," *Transactions of the Institution of Mining Engineers*, 1912, vol. 44, p. 145, Figs. 5 and 10.

(14) W. M. THORNTON: "An Electric Signalling Bell which does not Ignite Gas," *ibid.*, 1915, vol. 50, p. 19.

(15) J. A. WILCKEN: "Transient Phenomena at the Breaking of an Inductive Circuit," *Philosophical Magazine*, 1932, vol. 13, p. 1000.

(16) See Reference (1), p. 297.

(17) See an important series of papers in the *Proceedings of the Royal Society*, A, 1926–34, by Prof. G. I. FINCH and colleagues, on the electrical ignition of gases.

(18) See Figs. 4 to 8 of Reference (6).

(19) W. A. BONE: "Gaseous Combustion at High Pressures," *Philosophical Transactions of the Royal Society*, A, 1915, vol. 215, p. 289.

[The discussion on this paper will be found on page 161.]

THE RISK OF EXPLOSION DUE TO ELECTRIFICATION IN OPERATING THEATRES OF HOSPITALS

By E. H. RAYNER, M.A., Sc.D., Member.

[From the National Physical Laboratory.]

(*Paper first received 9th February, and in final form 8th June, 1937; read before* THE INSTITUTION *24th February, and before the* SCOTTISH CENTRE *8th March, 1938.*)

SUMMARY

Cases of ignition of anaesthetic vapours have occurred in hospitals which it has been difficult to account for except as a result of a spark due to unsuspected static electrification of the equipment used in operating theatres. Tests have been carried out in a number of hospitals, and it has been found that electrification of a frictional character, sufficient to produce a spark capable of igniting anaesthetic vapours, can often be generated in a simple manner. Measurements have been made in connection with methods suggested for the reduction of the risk to a negligible quantity. Phenomena are discussed which may lead to ignition due to the use of oxygen at high pressure.

The recent development of electrically-conducting rubber promises to afford a valuable preventive of static electrification.

A Bibliography has been compiled which indicates the seriousness of the risks associated with electrification.

(1) INTRODUCTION

In some cases of explosions of anaesthetics in operating theatres it has been suspected that the ignition was the result of static electrification of the equipment used in the theatre, with subsequent sparking sufficient to ignite the anaesthetics, gases, and vapours. This possibility was brought to the notice of the Department of Scientific and Industrial Research, which arranged for the question to be investigated at the National Physical Laboratory.

The risk of electrification is a serious one in America with its warmer and drier climate, and experience has shown that precautions are very necessary there if accidents are to be avoided. While the risk in this country appears to be much less, one or two disquieting incidents have taken place which made it desirable to obtain information of a more definite character than was available concerning the cause and prevention of dangerous conditions.

There are several uses of electricity in operating theatres which are potentially dangerous; but these have not been considered in the present paper, the problem being confined to the generation of static charges irrespective of any electrical supply. A pamphlet on the precautions to be taken in operating theatres on account of the general use of a variety of types of electrical apparatus has been recently issued by the Ministry of Health.*

The chief risk of ignition and explosion arises from the general use as an anaesthetic of ether and oxygen, mixtures of which are capable of ignition over a very wide range of proportion. Information obtained from America indicates that ethylene is used there to a considerably larger extent than appears to be the case in this country; and the use of cyclopropane is also increasing. Both these, as well as other gases and vapours, form explosive mixtures. The addition of nitrous oxide to a mixture of oxygen and ether or other similar anaesthetic vapour may increase considerably the violence of an explosion, on account of the liberation of the energy of dissociation of nitrous oxide into nitrogen and oxygen.

(2) PROCEDURE

In order to become acquainted with the conditions of the problem, visits have been paid to about twenty hospitals in this country and to one abroad. The subject has been discussed with the administrative and medical staffs, and with the nursing staff of operating theatres. Conferences have been held with public hospital authorities, information has been requested by announcements in the medical Press, and inquiries have also been made of hospital organizations in America.

(3) OCCURRENCE OF ELECTRIFICATION

Experiments and measurements which have been made in many of the hospitals visited have shown that a common possible cause of electrification which may become dangerous is of a "frictional" character. Electricity can frequently be generated without difficulty by the movement of fabrics over the surface of equipment commonly used in hospitals. The possibility of electrification depends upon some part of the equipment being adequately insulated, and rubber tyres commonly used for tables, patients' trolleys, anaesthetic and other apparatus, and sometimes for operating tables, are an important factor. Rubber mattresses an inch or more thick are commonly used, and also rubber sheets. The nature and electrical resistance of the floor has also to be considered.

A common mode of administering anaesthetic vapours is to use a stream of oxygen as a carrier. Oxygen from a cylinder at pressures up to 1 800 lb. per sq. in. passes through a hand-operated or automatic reducing valve, is bubbled through the anaesthetic liquid such as ether or chloroform, and passes on to a rubber face-piece covering the mouth and nose of the patient, or is administered by tube into the trachaea. Nitrous oxide is used from cylinders in a similar manner, and compressed carbon-dioxide is also kept available. The bubbling bottles are of glass, in order to enable one to see the rate of flow and

* "Precautions against Anaesthetic Explosions in Operating Theatres."

the quantity of liquid present, and the ether bottle is commonly provided with a surrounding metal bath for hot water, to increase the vapour pressure if required.

It will, perhaps, help to make the subject clearer to relate what has been considered to be the cause of the explosion of a mixture of ether and oxygen in the anaesthetizing room adjacent to an operating theatre in this country, an account of which has been published. The anaesthetizing apparatus with gas cylinders, etc., had been employed in the operating theatre for 2 hours, ether-oxygen mixture being used. The apparatus was brought out of the theatre into the anaesthetizing room adjacent to the theatre, where it was about to be used on a second patient who was lying on a rubber mattress on a trolley of metallic construction supported on rubber-tyred wheels. When the anaesthetizing apparatus, also mounted on rubber wheels, was brought close to the patient's trolley a violent explosion of the ether equipment took place. It was considered by one who has had wide experience of similar subjects and who examined the conditions of the case soon after the event, that the cause was probably a static spark. If this was so, it must have happened that the production of a spark took place at a point where there was a sufficient stream of ether and oxygen to propagate a flame or explosion. The chance of this happening was probably increased by the fact that the anaesthetic apparatus had been in use on a previous patient, and that ether was escaping from it more freely than would have been the case if it had not been in use for some time previously.

(4) EXPERIMENTAL PRODUCTION OF ELECTRIFICATION

Experiments carried out on the equipment of the hospital mentioned above showed that electrification sufficient to produce electric sparks could easily be produced by such methods as drawing a warm blanket across it. Similar results have been obtainable in most hospitals where experiments have been made. The production of electrification is frequently facilitated by the presence of rubber mattresses or sheets. While friction with woollen material is generally more efficacious in producing electrification than cotton, this has been found not to be always the case when experimenting with rubber materials.

The voltage which it is practicable to generate in this manner will depend upon the distance of the metal part of the structure from the floor, so that higher voltages may be obtainable if the equipment is mounted on thick rubber tyres than if it is mounted on thin or old ones in the cracks of which soap or other material of appreciable electrical conductivity is likely to have collected. The longest spark which has been produced in this manner has been of the order of 10–15 mm. Smaller sparks, from about 0·5 mm. upwards, have frequently been obtainable and it may probably be assumed that a discharge capable of being felt by the finger is an indication of conditions which may be dangerous. It is to be remembered that ether and oxygen form one of the most easily ignited combustible mixtures, and that the dangerous range of the proportion of ether to oxygen is very wide. In addition, combustion may commence at very low temperatures, possibly at 200° C. Any risk associated with ether is serious, as it is one of the most widely used anaesthetics. Its vapour density is more than double that of air, so that any escaping vapour tends to pour downhill in a concentrated stream carrying the oxygen with it. In fact ignition of ether vapour at floor level in operating theatres, due to the use of faulty electrical equipment, is not unknown.

(5) ELECTRICAL RESISTANCE OF FLOORS

It will be appreciated that electrification of the kind described depends upon equipment or persons being electrically insulated, and the use of rubber tyres on movable equipment is commonly capable of providing this condition. The nature of the floor is equally important, since, if it is a good insulator, there will be continual difficulty in discharging any chance electrification. The floors of operating theatres and anaesthetic rooms are nearly always of the "granolithic" type, in which a matrix of stone or marble particles is rendered solid, commonly by magnesium oxychloride. The top is ground smooth, providing an easily washable surface.

Measurements have been made of the electrical resistance of the floors in several hospitals, and they have all been found to have much the same value. Areas of tinfoil from 1 sq. in. to 25 sq. in. have been used, each pressed down on to the floor by a thick sheet of rubber with a weight on it. The resistance between the tinfoil and the water or heating system has been measured at 500 volts and found to be of the order of 2 megohms or less when using an area of 25 sq. in. The value does not vary much in different parts of a room. It may increase in the neighbourhood of radiators where the floor is locally kept warmer than the rest for long periods.

(6) METHODS OF PREVENTION OF ELECTRIFICATION

The method which has been used in America for avoiding the accumulation of dangerous charges is to attach a piece of light chain to the metal part of hospital equipment which may become charged, and allow a few inches of it to trail on the floor.

For the investigation of this method, measurements of the electrical resistance between varying lengths of chain on the floor have been compared with those obtained by the tinfoil method. The values are naturally higher, but the general result is that the use of a chain trailing for a few inches on the floor will reduce the value of any voltage attained by the equipment to one-tenth of its value in a time-interval of the order of 0·01 sec. or less. This value has been arrived at taking into account the electric capacitance of a man in parallel with that of a trolley carrying the anaesthetic equipment. The value has been found to be of the order of 0·0005 μF.

The practical effectiveness of the method has been shown by electrifying equipment so that a spark and a shock could be obtained from it, and then repeating the experiment with about 3 in. of chain trailing on the floor. In no case has any electrification been perceptible, and a pocket electrometer has also given no indication of charge. The same result has been obtained

on a theatre floor constructed of tiles. The chain need only be quite a light one and the links short, say $\frac{1}{4}$–$\frac{1}{2}$ in., so as to provide a large number of points of contact with the ground. It should be attached so as not to be stepped upon by the personnel when the apparatus is being moved.

In some hospitals rubber flooring is used in passages, etc., and occasionally in minor operating-theatres. Experiments have shown that the resistance of such floor coverings may be very high and that a perceptible charge may remain on the equipment for about 1 minute with a chain trailing on the rubber flooring. It is thus possible for two pieces of equipment to be charged to quite different potentials on an insulating floor and for a spark to occur between them when they are brought nearly into contact either directly, or indirectly through the hand of a member of the staff. It is to be remembered that rubber boots or goloshes are very frequently worn by all members of operating staffs of hospitals, and there is therefore the possibility of the personnel acting as carriers of appreciable charges and voltages, without being aware of it.

Experiments have shown that cork carpet is also a good insulator, and that a person may become electrified to 100 volts or more by walking a few steps on it. It has also been found that, in the case of cork carpet, wearing leather-soled shoes may be much more effective in producing electrification than wearing rubber-soled shoes. This kind of electrification, due to movement across a floor, is almost commonplace in America, with its dry Continental type of climate. In some hospitals there the theatre personnel are fitted with trailing chains, and metal strips are let into the surface of the floor every few inches to provide a means of keeping the chains at earth potential. The serious and occasionally tragic results of explosions have not unnaturally led to the use of every possible precaution.

(7) EFFECT OF HUMIDITY

The generation of electrification by friction of fabrics, etc., is much facilitated by a dry atmosphere. The driest conditions are attained in very cold weather in a dry climate, when the external air contains very little moisture. This air may be heated through a range of 50 deg. C. before use in the operating theatre, so that the relative humidity (degree of saturation) is very low. Artificial increase in the humidity is required to ensure safety; and there is definite experimental evidence from America that if the relative humidity is not below 65 % the danger becomes relatively very small. It is to be noted that a "conditioned" atmosphere, in which the air is commonly filtered and washed, may lead to a lower humidity than air which is not washed. Cold washing water, if cooler than the air, may extract moisture from it by cooling it below the dew point, and the washed air when warmed to the original temperature will be drier than the original fresh air. In winter it will be raised to a higher temperature, with the risk indicated above. This factor may be of some importance in this country, on account of the growing use of conditioned air; and, while it may be to some extent a coincidence, two of the hospitals where electrification has been found to be most easily produced and which have had trouble due to anaesthetic ignition, have been equipped with air-conditioning plant.

(8) GENERATION OF ELECTRICITY IN ANAESTHETIC APPARATUS

There is the possibility of electrical charges being generated in the anaesthetic equipment.

As has been described above, the common type uses oxygen or nitrous oxide from a high-pressure cylinder passing through automatic or hand-operated reducing valves, and through bubbling bottles containing water, ether, chloroform, etc., with suitable valves for bypassing the unwanted anaesthetics. Elastic rubber breathing-bags are also commonly used.

Experiments have been made to see whether any electrification resulted from bubbling oxygen through ether. None could be detected. There is a considerable amount of rubber tubing and equipment in the gas stream. If this is subjected to friction such as may occur during the expansion and contraction of breathing bags, electrification may be produced. A considerable amount of experimental research on a variety of equipments, under various conditions, would be required to estimate the importance of this possible source of electrification. So far the external sources seem to have been sufficient to account for the accidents which have happened in this country. There appears to be an impression in America that electrical discharges generated by the anaesthetic apparatus are largely responsible for anaesthetic ignitions, but no definite technical information on the subject has been found. They may be associated with the phenomena discussed in the next Section. Apparatus naturally varies from one country to another, and differences in mechanical details and in physical conditions may have an important effect on the degree of risk.

(9) GAS VALVES

An important possible source of generation of an electric charge when compressed gas is being used arises from the interaction of solid or liquid particles and a stream of gas. One example of this is the breaking-up of large drops of rain, forming smaller ones as they fall through the air. The breaking-up gives rise to an electric separation to which may be ascribed the origin of lightning. If compressed gas in a cylinder becomes contaminated with liquid particles and blows them along at a velocity of a few hundred feet per second, a notable amount of electrification can be produced. A gauze of metal wires placed in the gas stream may become charged to several thousand volts. The effect disappears if the temperature is raised so that the liquid is vaporized and the gas stream is free from particles.

A very small amount of moisture in oxygen at atmospheric pressure before compression into a cylinder will give rise to a much greater relative humidity at the normal pressure of 120 atmospheres. If condensation results, the condensate is likely to collect at the valve if the cylinder is stored or used in a horizontal position. These factors indicate the importance of using cylinders in a vertical position with the valve at the top, and

taking the precaution to blow off a small amount of gas before attaching reducing valves, etc., to them.

While electrification may be produced by a sudden discharge of a gas containing fluid particles, or containing vapour which may give rise to particles through the temperature-changes involved in the discharge, it seems very unlikely that electrification of this type will cause trouble with anaesthetics when the apparatus is actually working, after passing through the initial conditions associated with the turning-on of the high-pressure gas. The velocity is much less than that at which serious electrification has been obtained in experiments when relatively large amounts of fluid have been added deliberately to the gas stream.

Similar electrification results from dust in a gas stream, and high-voltage generators have been constructed on this principle. When oxygen is used there is the additional risk of the particles of dust, dirt, or grease being ignited, which may be facilitated by the thermodynamic temperature variations which occur in the passage of a high-pressure gas through regulating valves, etc. It is to be noted also that in automatic regulating valves used in this country the operating element which shuts off the high-pressure gas is made of ebonite. Experience has shown this to be the most suitable material for the purpose.

Explosions have been known to occur in such reducing valves in hospitals when using oxygen, and the valve seating to be burnt away, sometimes igniting the rubber diaphragm which forms part of the mechanism. There is then nothing to restrain the discharge of the oxygen. When the gas is being used for other purposes the result may be little more than an inconvenience, but if the explosion reaches an anaesthetic vapour the result may be very serious. It is therefore important to be particularly careful to turn on gas valves of cylinders slowly, especially when they are full and when they are being used for the first time after reducing valves have been attached to them. At least one reducing-valve explosion in a hospital has occurred on opening the main valve of a full cylinder of oxygen, after changing over the reducing valve from a cylinder which became empty during the course of an operation.

(10) RUBBER OF LOW ELECTRICAL RESISTIVITY

The risk of electrification is largely dependent on the use of rubber for tyres, mattresses, sheets, tubing, etc., and it would be much reduced if rubber of an appreciable electrical conductivity were available.

A conducting type of rubber has recently been developed by the Dunlop Rubber Co. The Company were consulted on the practicability of this product being used for anaesthetic apparatus, and they provided for inspection samples having resistivities varying from several megohms down to a few ohms. The method of producing the electrical conductivity appeared to have no effect on the general properties of the material. It seemed so promising that the Company were invited to make up samples of the more special types of rubber equipment used in anaesthetic apparatus, the resistance of the objects to be of the order of 1 megohm. They have produced a sample of the corrugated rubber tubing commonly used for connecting the face-piece to the anaesthetic apparatus: this is about 1 m. long, 30 mm. diameter, and 1 mm. thick, the resistance between the ends being about 1 megohm. They have also made a breathing bag of the usual type: this has a resistance of about 0·5 megohm between the ends.

The tube has been subjected for 6 hours to a stream of ether vapour, to one of chloroform vapour, and to a mixture of the two. Samples have been soaked in 5 % lysol for 20 hours, followed by boiling for 4 hours. No appreciable alteration in conductivity was produced by any of these treatments.

The substitution of this type of material for ordinary rubber promises to provide an effective method of preventing dangerous voltages of a static character being attained in the use of anaesthetic apparatus.

By the phrase " rubber of low resistivity " is meant a value low in comparison with that of natural rubber, which is very high compared with a value of 1 megohm. It is desirable to maintain a fairly high value for the resistance of items of rubber equipment, say 100 000 ohms and upwards. If a value of the order of 100 ohms were used, and the object came into contact with an electrical supply of 230 volts, the power absorbed would be about 500 watts, which would be likely to cause ignition in a few seconds, without the current being large enough to melt an ordinary circuit fuse.

(11) OTHER POSSIBLE SOURCES OF IGNITION

This paper only deals with the production of electrification by " frictional " means, leading to sparks which may ignite explosive mixtures. There are many uses of electricity in surgical operations, and small defects in the apparatus used may lead to equally serious explosions. Among them are lamps for internal and external illumination, high- and low-frequency cautery apparatus, motors for suction pumps, and bone saws. Only the observation of the most stringent rules as regards design, maintenance, and use, will prevent trouble due to such equipment igniting anaesthetic vapours.

(12) RESULTS

The results of the investigations which have been carried out may be summarized as follows:—

(i) The movement of dry fabrics, such as the removal of a blanket from a patient or trolley, may result in dangerous electrification of the equipment.

(ii) The risk becomes very small if the humidity is as high as 65 %, but a warm blanket from a hot cupboard may require a long time to attain hygrometric equilibrium with the surrounding atmosphere.

(iii) It is very important and desirable to make arrangements to discharge any electrification of operating tables, trolleys, or anaesthetic machines, by the provision of " earthing chains " trailing on a semi-conducting floor, such as the granolithic type.

(iv) Instead of an earthing chain, conducting rubber promises to be a valuable material.

(v) The possibility of defective action of high-pressure gas equipment giving rise to ignition or explosion must be kept in mind.

The work has been carried out in consultation with the Anaesthetics Committee appointed jointly by the Medical Research Council and the Anaesthetics Section of the Royal Society of Medicine.

BIBLIOGRAPHY

Sir H. DAVY: "Some New Experiments and Observations on the Combustion of Gaseous Mixtures; with an Account of a Method of Preserving a Continued Light in Mixtures of Inflammable Gases and Air without Flame," *Philosophical Transactions of the Royal Society*, 1817, p. 77; *Journal of the Royal Institution*, vol. 5 (i), Preface.

GILBERT: "Phosphorescence of Burning Ether," *Annalen der Physik*, 1817, vol. 26, p. 245.

GMELIN: "Phosphorescent Combustion of Ether," *Handbook of Chemistry*, 1846, vol. 8, p. 178.

W. H. PERKIN: "Some Observations on the Luminous Incomplete Combustion of Ether and other Organic Bodies," *Journal of the Chemical Society*, 1882, vol. 41, p. 363.

E. von NEANDER: "Ether Explosions Facilitated by Impurities," *Chemische Zeitschrift*, 1902, vol. 26, p. 336; *Chemical Society Abstracts*, 1902, vol. 82 (i), p. 527.

G. KASSNER: "An Ether Explosion," *Archiv der Pharmazie*, 1912, vol. 250, p. 436; *Chemical Society Abstracts*, 1912, vol. 102 (i), p. 826.

E. ALILAIRE: "Low-Temperature Combustion of Ether and Air," *Comptes Rendus*, 1919, vol. 168, p. 729; *Chemical Society Abstracts*, 1919, vol. 116 (i), p. 194.

A. G. WHITE and T. W. PRICE: "The Ignition of Ether-Alcohol-Air and Acetone-Air Mixtures in contact with Heated Surfaces," *Transactions of the Chemical Society*, 1919, vol. 115 (ii), p. 1462.

J. A. MCCLELLAND and H. V. GILL: "An Investigation into the Causes of the Self-Ignition of Ether-Air Mixtures," *Proceedings of the Royal Dublin Society*, 1920, vol. 16, p. 109; *Chemical Society Abstracts*, 1920, vol. 118 (ii), p. 676.

A. M. CLOVER: "The Autoxidation of Ethyl Ether," *Journal of the American Chemical Society*, 1922, vol. 44, p. 1107.

A. B. LUCKHARDT: "The Potential Dangers attendant on Ethylene-Oxygen Anesthesia," *Journal of the American Medical Association*, 1924, vol. 82, p. 1603.

C. H. DAVIS: "The Explosibility of Ethylene," *ibid.*, 1924, vol. 82, p. 1607.

"Danger of Explosion," *Die Chemische Industrie*, 1924, p. xiv (Supplement).

W. B. LEWIS and E. F. BOEHM: "A Simple Method of Eliminating Danger of Explosion due to Static Spark in Gas-Oxygen Apparatus," *Journal of the American Medical Association*, 1925, vol. 84, p. 1417.

ISABELLA C. HERB: "Explosions of Anaesthetic Gases," *ibid.*, 1925, vol. 85, p. 1788.

"An Unusual Anaesthetic Fatality," *British Medical Journal*, 1925, vol. (ii), p. 713.

C. F. HADFIELD: "Ignition of Ether at Low Temperatures," *Lancet*, 1926, vol. (i), p. 258.

E. I. MCKESSON: "How Can We Eliminate Static from Operating Rooms to Avoid Accidents with Anaesthetics?" *British Journal of Anaesthesia*, 1926, vol. 3, p. 178.

J. BLOMFIELD: "Recent Investigations concerning Nitrous Oxide, and the Ignition Points of some Anaesthetic Vapours," *Proceedings of the Royal Society of Medicine*, 1926, vol. 19, p. 39.

H. B. DIXON: "The Burning of Gases in Nitrous Oxide," *Memoirs and Proceedings of the Manchester Literary and Philosophical Society*, 1926, vol. 71, p. 15.

"The Dangers of Gaseous Anaesthetics," *Lancet*, 1927, vol. (i), p. 240.

H. B. DIXON: "The Ignition Points of Gases in Nitrous Oxide," *ibid.*, 1927, vol. (i), p. 247.

ISABELLA C. HERB: "Further Clinical Experiences with Ethylene-Oxygen Anaesthesia," *Anesthesia and Analgesia*, 1927, vol. 6, p. 258.

H. DEMUS: "Warning concerning Working with Ether," *Zeitschrift für angewandte Chemie*, 1928, vol. 41, p. 426.

A. P. HORNER and C. V. GARDENIER: "A Means of Intercepting Explosions in Anaesthetics," *Anesthesia and Analgesia*, 1928, vol. 7, p. 371.

R. D. HOBBS: "Suggestions for Safeguarding the Operating Room," *The Modern Hospital*, 1929, vol. 32, p. 86.

C. H. WARDELL: "Minimizing the Fire and Explosion Hazard of Anaesthetic Agents," *Anesthesia and Analgesia*, 1929, vol. 8, p. 95.

H. B. WILLIAMS: "The Explosion Hazard in Anaesthesia," *Journal of the American Medical Association*, 1930, vol. 94, p. 918.

P. L. HOOVER and E. C. CUTLER: "Eliminating the Explosion Hazard in Operating Rooms," *The Modern Hospital*, 1930, vol. 35, p. 49.

K. B. PINSON: "Anaesthetic Explosions," *British Medical Journal*, 1930, vol. (ii), p. 312.

Report (with about 50 references), on "The Hazard of Explosion of Anaesthetics," *Journal of the American Medical Association*, 1930, vol. 94, p. 1491; also *British Medical Journal*, 1930, vol. (i), p. 1062.

H. W. FEATHERSTONE: "Discussion on Anaesthesia for Diathermy and Endoscopy," *Proceedings of the Royal Society of Medicine*, 1931, vol. 25 (i), p. 119.

J. D. MORGAN: "A Note on the Inflammability of Combustible Gas Mixtures, with Special Reference to Anaesthetic Ether-Air and Ether-Oxygen Mixtures," *ibid.*, 1931, vol. 25 (i), p. 123.

H. R. GRIFFITH: "Operating-Room Explosions," *Anesthesia and Analgesia*, 1931, vol. 10, p. 281.

"Safety in Hospitals" (National Safety Council and American Hospital Association, January, 1933).

VON SCHEURLEN: "Explosion of Anaesthetics," *Zeitschrift für ärztliche Fortbildung*, 1933, vol. 30, p. 70.

C. J. GAUSS and C. MARGRAF: "Precautions against Risk of Static Electrification and Explosion," *Deutsche medizinische Wochenschrift*, 1933, p. 597.

"Anaesthetic Explosions," *British Medical Journal*, 1933, vol. (i), p. 969.

W. SCHULTZ: "Ether Explosion when Anaesthetizing with the Roth-Dräger Apparatus," *Schmerz, Narkose-Anaesthesie*, 1934, vol. 6, p. 98.

H. SCHROEDER and T. C. NEEF: "Frictional Electricity as a Cause of Anaesthetic Explosion, and its Prevention," *ibid.*, 1934, vol. 6, p. 103.

R. IRONSIDE: "An Explosion in Anaesthetic Apparatus," *Proceedings of the Royal Society of Medicine*, 1935, vol. 28, p. 1127.

C. F. HADFIELD: "The Joint Anaesthetics Committee: a Retrospect of Eleven Years' Work," *ibid.*, 1935, vol. 28, p. 1133.

G. I. FINCH: "The Electrical Ignition of Explosive Anaesthetic Mixtures," *ibid.*, 1935, vol. 28, p. 1130.

"Account of Air-Conditioning Plant," *Bulletin of the Society of the New York Hospital*, July and August, 1935.

W. RIMARSKI and FRIEDRICH: "Electrostatic Charges in Flowing Gases," *Proceedings of the Twelfth International Congress of Acetylene and Oxy-Acetylene Welding, London*, 1936, vol. 4, p. 912.

G. EDWARDS: "The Ideal Structure of an Operating Theatre from the point of view of an Anaesthetist," *Proceedings of the Royal Society of Medicine*, 1937, vol. 30, p. 331.

DISCUSSION ON THE PAPERS BY PROFESSOR THORNTON (SEE PAGE 145) AND DR. RAYNER (SEE PAGE 156)

BEFORE THE INSTITUTION, 24TH FEBRUARY, 1938

Mr. H. W. Swann: Although we seldom hear of explosions of anaesthetics, and in many ways I think it undesirable that we should hear of them, I believe our friends—the surgeons and the anaesthetists—realize the risk and join me in appreciating the value of the authors' work.

About 4 years ago the Ministry of Health collected information on this risk from various sources and learned of 23 cases of explosion in recent years which were attributed to electrical ignition in some form or other. There were probably more than this, but of the known cases 14 caused fatalities and 7 were attended by injury. I was asked to collaborate on the electrical side, and after some visits to hospitals and many most interesting discussions with surgeons and anaesthetists I came to the conclusion that risks were unknowingly and often unnecessarily incurred and that some electrical research work was needed.

I was at that stage much indebted to Dr. C. C. Paterson and Mr. E. B. Wedmore, and later to the Anaesthetics Committee of the Medical Research Council, for creating the necessary interest to initiate the researches which have since been undertaken by Prof. Thornton and Dr. Rayner. I should like also to express my acknowledgments for the subsequent assistance which has been received from Dr. Townend, and from Dr. Saunders, who will, I believe, presently refer to some experiments he has made and offer some valuable suggestions. I am also indebted to Mr. Harper, who has made measurements of the temperatures attained by the glass bulbs of surgical lamps when over-run, which I hope he will mention shortly. There are many others to whom my thanks are due for direct or indirect assistance. In fact, my efforts have been confined to persuading others to do the work, and the only item I tried to contribute myself—that of an ether extraction fan with a pipe of which the inlet was intended to be applied near the patient's head to remove the inflammable gas—turned out to be a failure on account of the excessive noise.

I think the two main questions which arise on Prof. Thornton's paper are the degree of safety achieved by the circuit limitations and the utility of the lamps under the conditions laid down. On the first, the paper describes a number of experiments which show that under many conditions circuit constants can be stated within which the risk of explosion is greatly reduced; but I am still anxious about a hot spot in a flexible, such as may occur just before the moment of breakage, and the predisposing effect of this and of an over-run lamp. The question of the utility of these lamps is more for a surgeon than for me, and I have endeavoured to get them tried in practice. The light-reducing effect of the added resistance may be compensated by using a lamp of lower voltage than the source of supply, but although an intrinsically safe circuit is independent of lamp resistance as regards spark ignition, a 2-volt lamp can, I think, still be dangerously over-run on a 6-volt circuit despite the limiting resistance.

Dr. Rayner deals not only with the way in which static charges may be set up but also with methods of dispersal. In this connection I have been impressed with the possibilities of conductive rubber, but it is rather important that the specific resistance should not be low enough to introduce risk of fire should a leakage of electricity occur from any electrical current-consuming apparatus, which may, for instance, stand on a floor covered with conductive rubber.

I should like to conclude by saying that both the papers and, I believe, the discussion which is to follow, will show that there is a need for a joint technical body to deal with the design of electro-surgical appliances and with the provision of some means of testing them from the point of view of use in inflammable atmospheres. There are already in existence laboratories where the organization is suitable for this class of testing work, and I feel that unless some organized effort on the lines indicated is made, much of the value of the work represented by the two papers will be lost.

Dr. C. F. Hadfield: Explosions attributable to static electricity have unfortunately become common of late. For many years I had been accustomed to write and teach students that, while static electricity might be a danger in dry and cold countries like the U.S.A., it was quite harmless in our own more humid climate. I have been shown to be wrong, and I am convinced that this is partly if not wholly due to the love of modern hospital architects for conditioned air, which is usually dry and must aid the development of static sparks. Again, architects now take the greatest care to exclude from the operating theatre any trace of steam from the sterilizing apparatus next door. The very dry atmosphere thus assured certainly adds somewhat to the

comfort of the surgeon, by diminishing his own sensible perspiration; on the other hand, by increasing the loss of fluid from the exposed surfaces of the patients' body it tends to add to the risk of operative shock. It is interesting to note that while our own hospital authorities have spent money on drying the air in their operating theatres in the ways which I have mentioned, the Americans have devised humidifiers for maintaining adequate moisture-content in theirs.

Probably few people realize that the practice of anaesthesia is not yet 100 years old. It was only in the forties of the last century that nitrous oxide, ether, and chloroform, were used as anaesthetics, and of these ether alone is inflammable. The risk involved in its use has, I think, always been recognized. Nitrous oxide had until recently been regarded as a particularly inert and safe gas, but only a few years ago the late Prof. Dixon, working for the Anaesthetics Committee, was able to show that although it is not inflammable, nitrous oxide is able under suitable conditions to support the ignition of other gases even more actively than pure oxygen.

For many years nitrous oxide, ether, and chloroform remained the only agents at the disposal of anaesthetists, and only recently have other gases been used for inhalation anaesthesia. These gases are mainly post-War developments, and it is unfortunate that they are all inflammable and, under suitable conditions, explosive. I am not aware that the ignition of ethyl chloride has ever caused serious trouble. Ethylene, though still much used in America, soon lost favour in this country, partly through its objectionable smell and partly on account of the risk of explosion. Modern methods of closed-circuit anaesthesia, however, combined with carbon-dioxide absorption, have diminished the risk and enabled a still more recent medium, cyclopropane, to become a useful and important anaesthetic. I believe that suitable combinations of ethylene or cyclopropane with oxygen are equally inflammable and more disastrously explosive than oxygen-ether mixtures. Except for certain special purposes, chloroform is no longer used by skilled anaesthetists, so that all our major anaesthetic agents are inflammable and explosive, or at least support combustion.

Prof. Thornton's paper states: "For most of the purposes for which anaesthetics are required inflammability is not of the first importance, but for certain operations on the mouth and throat, in which electric lamps and cauteries are used, experience has shown that there are risks of ignition of the anaesthetic mixture." I would point out that the risks of explosion from the causes named are by no means limited to such a small class of operation. The surgeon has so many electromechanical appliances of all kinds at his disposal to-day that there are very few operations in which the anaesthetist can take the risk of allowing his patient to be surrounded by an intrinsically explosive atmosphere. I would especially emphasize the danger of foot switches. These tend to give sparks and are situated on the floor, where any heavy ether vapour will accumulate.

It is particularly unfortunate that, with the increasing use of explosive anaesthetics, surgeons have become more enamoured of the use of diathermy, with which a certain amount of sparking cannot be avoided and therefore the use of inflammable anaesthetics is unjustified. This is particularly to be regretted in the rapidly-developing field of lung surgery, for which cyclopropane is the almost ideal anaesthetic and diathermy almost the ideal cutting method, yet they cannot be used together. There would be a wonderful field of usefulness for an anaesthetic gas comparable to cyclopropane but not inflammable; that any such gas remains to be discovered is, I fear, highly improbable.

Dr. D. T. A. Townend: I am sure that Prof. Thornton's investigation will be of value to those interested in combustion problems generally, and that it will also ultimately go far towards eliminating the risks inherent in the use of ether as an anaesthetic. At South Kensington we have also been studying the combustion of ether over the last few years, but from rather a different aspect. Ether is representative of those fuels which give rise to "knock" in internal-combustion engines. In particular, it gives rise to that peculiar type of combustion which is usually referred to as a cool flame, and we now recognize that those fuels which give rise most easily to "knock" in an engine do so because the cool-flame type of combustion is first developed in the unburnt mixture ahead of the explosion flame. While with petrol fuels it is only possible to study the cool-flame combustion under conditions of a few atmospheres pressure, with ether it may be examined at atmospheric and reduced pressures.

Cool flames were observed, I think, by Humphry Davy more than a century ago, and were examined in more detail by W. H. Perkin in 1882, but we still know very little indeed about them; renewed interest in the subject was aroused by a paper by Dr. A. G. White from Nobel's laboratory at Ardeer in the year 1922 or thereabouts. Dr. White determined the limits of inflammability of ether-air mixtures in horizontal glass tubes and discovered that in the circumstances of his experiments there were two ranges of inflammability. There was a range of inflammable mixtures for the normal flame between about 3 and 9 per cent of ether in air (AB in Fig. A) and a quite distinct range for the cool flame between about 19 and 34 per cent of ether in air (CD in Fig. A). I ought also to explain that the range for the normal flame was obtained by the use of high-voltage sparks, or what are described as fat sparks. It is a matter of great importance that such a spark is not capable of igniting a cool flame at atmospheric pressure. To initiate a cool flame it is necessary to use a hot wire; the reason for this I will explain later on.

As one passes across the normal-flame range from the low limit (A) the mixture becomes richer in combustible, and the intensity of an explosion more violent; in the case of the theoretical mixture for complete combustion the explosion is very violent, but ultimately the explosions become less violent again as the upper limit of inflammability (B) is approached. One can hardly see the cool flames; it is imperative to work entirely in darkness, and the flames travel very slowly, with a speed of something like 20 cm. per sec. in a tube $3 \cdot 5$ cm. in diameter; combustion in the cool flame is also very incomplete and the gaseous products smell strongly of intermediate compounds, notably acetaldehyde. The flames therefore differ entirely from normal ones, and

unless they are studied in the dark it is quite impossible to be aware of their existence.

The matter rested there for about 5 years, and then Dr. White studied the effect of reduced pressure on these ranges, and discovered that there were two distinct systems, one for each type of flame, and the systems overlapped at about atmospheric pressure. The system for the normal flames centred upon the theoretical mixture for complete combustion, and that for the cool flames upon approximately the mixture containing an ether : oxygen ratio of 1 : 1.

Our interest in this work lies in the study of the behaviour of the flames in ether-air mixtures under conditions when the two flame systems overlap, and thus particularly when one goes to higher pressures. At South Kensington we therefore took up the problem from this point of view.

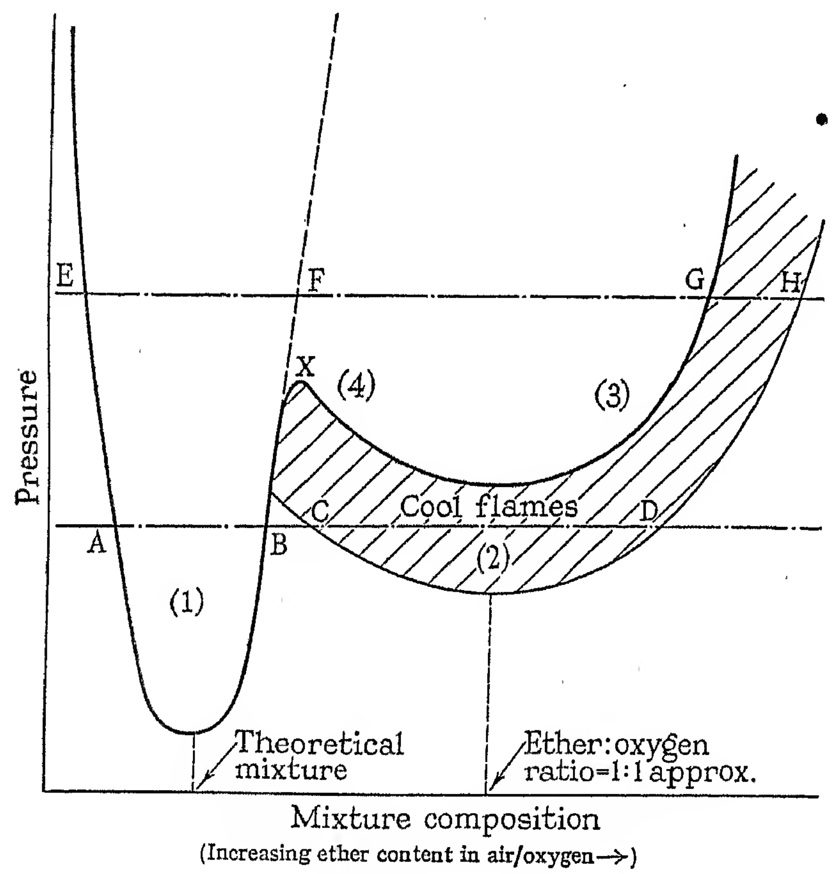


Fig. A

It was soon discovered that when the experiments were carried to high enough pressures the cool flames gave rise to a separate normal-flame range; so that if we define the new limits for these flames by the curve XG, the complete range for normal flames becomes EABXG and for cool flames the outer area defined by the boundary CDH. It is important to remember, however, that the normal-flame ignitions in the range FXG are always preceded by a cool flame, even though its duration may be far too brief for accurate observation. Much the same type of system is found whether the experiments take place in air or in oxygen, though with the latter the ranges are naturally much wider and the full ignition range is developed at pressures below atmospheric.

At atmospheric pressure with ether-air mixtures Prof. Thornton has crossed the dual system along the path ABCD. He has defined the range AB by means of coil sparks, break sparks, or heated wires; the cool-flame range CD would only have been detected by means of hot-wire ignition and in complete darkness. With ether-oxygen mixtures the dual system would have been crossed at atmospheric pressure along the path EFGH. In this case the range EF was again defined by coil sparks, and break sparks. The whole range EG, however, was now defined by hot wires, for with the oxygen-diluted media the cool flames initiated in the range FG would give place at once to normal flames.

Prof. Thornton's results are in close agreement with our own work on these ranges, the only point of interest being that he could not have located the wider range with the air-diluted mixtures because under his conditions of working he probably would never have detected the cool flames.

We have brought with us some tubes of explosive ether mixtures, and I hope to show one or two of the effects I have just described. They are difficult to reproduce in a hall like this, because the explosions are very sensitive to pressure conditions, and we have had to store these mixtures for some time, there being a slight risk of a little air-leakage into the tubes. All the explosions will be at reduced pressures, to avoid any risk of the tubes breaking.

Experiment 1.—The first tube contains a mixture of ether and air at reduced pressure corresponding with the location (1), Fig. A, in the inflammable range. The explosion flame will be whitish, typical of the normal flame in a mixture containing an excess of combustible over the theoretical proportion.

Experiment 2.—We now show the cool flame passing through a mixture of pressure and composition located at (2) in Fig. A. We need complete darkness; the flame will travel very slowly indeed, and only just be visible.

Experiment 3.—This experiment is to show how a normal ignition arises after the initial formation of a cool flame. The mixture is of ether and oxygen, located at (3), and its behaviour would be typical of the extended range of mixtures covered by Prof. Thornton when employing hot-wire ignition.

Experiment 4.—The mixture in the last experiment is of ether and oxygen, located at (4). First, a cool flame will be initiated and pass quietly along the tube. After it has travelled some distance the normal flame will suddenly make its appearance behind the cool flame in the gaseous products left behind, and the succeeding part of the explosion will be very violent, at any rate as violent as can be risked in this meeting. My point in showing this experiment is to demonstrate how dangerous in certain circumstances the formation of a cool flame may be, for it may be initiated in an open room without any one being conscious of its presence and may travel quite harmlessly over a considerable distance; on encountering a more explosive mixture, or in other suitable circumstances, however, it may give place to a violent explosion.

(*Communicated*) Time at the meeting did not allow of my discussing the important difference in the methods of igniting the normal and the cool flames. The cool flames appear to have an upper temperature-limit of about 270° C.; their existence seems to depend upon the thermal stability of an, as yet, unidentified intermediate compound. In ignition-temperature experiments, cool

flames can only be initiated by contact with the hot walls of a containing vessel if the latter are between approximately 170° and 270° C.; higher or lower temperatures are ineffective. It seems likely, therefore, that the energy of an ordinary spark is sufficient to cause the thermal decomposition of the material essential to the cool-flame process, and the interesting problem now presents itself of ascertaining whether there is a range of *weak* spark intensities at atmospheric pressure capable of initiating cool flames.

I would express my indebtedness to my collaborators, Mr. M. Maccormac and Mr. E. Wygard, who were entirely responsible for the success of our experiments.

Mr. C. T. A. Harper: Mr. Swann has referred to the results of work which we were asked to do in connection with the very small lamps used in nose and throat operations, and operations on other parts of the body. The question put to us was: What is the temperature which is reached by these little lamps? We found that in some of the cases a temperature approaching 250° C. was reached before the lamp failed. I understand that a temperature in the region of 200° C. is rather dangerous where explosive gas mixtures are present. In these experiments we had some cotton thread wrapped round some of the lamps, and we noticed that this started to char at a voltage corresponding to 200° C.

These results indicate that arrangements should be made to prevent the surgeon from overrunning these small lamps. In no case did breakage of the lamp bulb occur; this is comforting, because in the event of such a breakage at the higher temperatures incandescent metal might be released, which of course would be certain to cause an explosion.

Dr. H. L. Saunders: It was at the request of Mr. Swann that I was invited to check some of Prof. Thornton's figures relating to fizzling sparks, and I should like to give a brief description of the apparatus used and the results obtained.

The apparatus was a glass tube with side arms holding rubber-mounted electrodes, to the ends of which were soldered pieces of flexible conductor. The tube was 17 cm. long and 3·5 cm. in diameter, and was fitted with ground-glass end-plates. Between the end of the tube and the plate was placed a cellophane diaphragm. The tube was filled with the explosive mixture by first of all evacuating it and then admitting (and measuring the partial pressures) ether, air, and oxygen as required. One of the plates was slipped off, leaving the cellophane diaphragm holding the mixture. By this means it was possible to explode as many mixtures as desired without breaking the tube.

The range of mixtures studied covered ether in air, and ether in enriched air up to 4 times the normal oxygen-content. This was suggested as being likely to cover most of the cases where explosions had previously been known to occur in anaesthesia work. The ratio of ether to oxygen varied between 1 : 3 and 1 : 6.

So far as fizzling sparks alone were concerned, the a.c. circuits were found in all cases to be safe, but the same was not always so with the d.c. circuits.

Although the normal form of the discharge between the ends of the flexible (14/36 S.W.G.) was a succession of sparks from the point contacts, a special case arose where the circuit was completed through only a single strand of the conductor; when, under certain conditions, the temperature of the ether mixture was raised locally above the ignition point and an explosion occurred, although the same mixtures were not ignited by a train of sparks from the pieces of flexible. An intermittent contact—involving a combination of the heating effect and the spark—is undoubtedly the most insidious cause of explosions, for in this case the temperature of the gaseous mixture in the vicinity of the spark may be raised considerably, though still insufficiently to cause ignition, in which event a much smaller energy-input via the spark is necessary to cause an explosion. The extent of the local heating depends on many factors, such as convection currents and the size of the conductor, and will vary according to the nature of the contact and the rate of heat dissipation away from the heated zone. A finer-stranded flexible, such as I believe is sometimes employed in the connections to surgical lamps, might be more dangerous than the flexible I have mentioned.

There were one or two cases which gave inconclusive results because of another effect, due, I think, to surface combustion of the ether-air mixture upon the wire. This results in oxidation of the wire, which then limits the energy of the spark.

I should like to suggest that flexible conductors should be tested from time to time by resistance measurements carried out whilst the flexible is held under tension.

Furthermore, in connection with the surgical lamps, the ignition temperature in the air-oxygen mixtures is only of the order of 180°–280° C., and we have heard that the temperature of the glass of the bulbs can often exceed that limit. I do not think it should be beyond the capacity of the lamp-makers to vacuum-jacket these surgical lamps, on the principle of the Dewar flask, and thus reduce the risk of the outside temperature rising to a dangerous value.

Prof. S. Russ: On reading Prof. Thornton's paper I was prompted to inquire whether engineers used the terms " arc " and " spark " more or less indiscriminately. Physicists generally reserve the term " spark " for anything over the minimum sparking potential, but the potentials quoted in this paper for the current circuits were all below that level. I therefore take it that in many of the cases mentioned the author is thinking about arcs and not sparks.

We have tried deliberately to provoke an explosion with small surgical lamps, but have not succeeded. We put a lamp inside a glass bulb, shown in Fig. B, and round it a thermo-electric junction of eureka and copper to measure the temperature. We then introduced the explodable mixture and gradually raised the temperature till the filament fused. Even with highly explodable mixtures there was no explosion. No doubt the surface temperature depends on the thickness of the glass.

We cut a few of these lamps open to measure the thickness of the glass, and found that it could be as low as 0·19 mm. or as high as 0·33 mm. We suggest that before the manufacturers issue these lamps for medical use they should see that the surface temperature which is going to result with the maximum current is kept within safe limits. Table A gives some measurements

made on the temperature of the air surrounding the lamps.

We also mounted electrodes inside our explosion vessels and struck an arc between them. Like Prof. Thornton, we found that the ordinary current which would be taken by these lamps was quite inadequate to cause an explosion; from 0·7 to 0·8 amp. was necessary before an explosion would occur. The limitations are therefore quite definite, and, I think, could themselves be made great factors of safety.

I should like to suggest that The Institution should form an Operating Theatre Safety Committee. With the knowledge at its disposal it would not be too difficult a matter to draw up some recommendations for general use to obviate the dangers attendant on the use of electric circuits of all kinds in operating theatres. Some years ago a committee was formed to secure greater safety in X-ray and radium work. The recommendations of that committee have been very largely followed in this as well as in other countries. It has been found that although these recommendations cannot be enforced legally, they have been very generally accepted by those who have a sense of responsibility towards the safety of others.

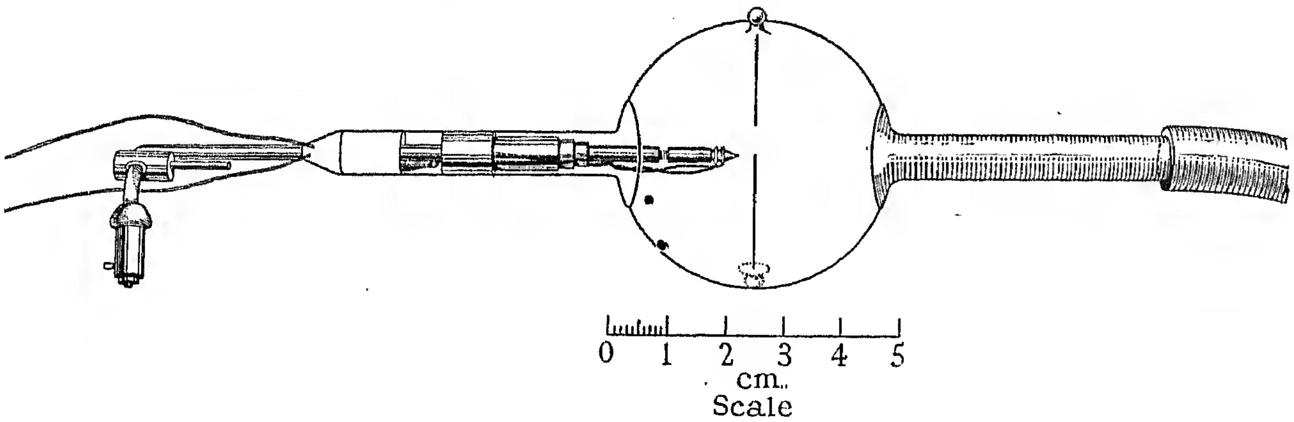


Fig. B

Table A

Lamp No.	Current through lamp	Resistance of lamp	Temperature of air surrounding lamp
	amp.	ohms	°C.
1	0·14	23·5	44
2	0·19	21·0	98
3*	0·18	22·0	96
4	0·19	20·5	55
5*	0·15	26·6	90
6	0·18	20·0	58
7*	0·22	18·0	172

* These lamps did not give an intensity of illumination equal to that of the standard lamp.

Dr. C. Langton Hewer: The question of safety in operating theatres has to be tackled from three aspects: first, the source of ignition; secondly, the ignitable mixture; and thirdly, the means of separating one from the other.

Sources of ignition can be divided from the practical point of view into three classes. The first is static electricity: the usual protection from this which is now given by trailing chains seems to be quite adequate, and since those precautions have been taken there has probably not been in this country an explosion attributable to static electricity. The second class is non-static sparks, and especially diathermy sparks, which will ignite explosive mixtures very readily. Lastly, we have the overheating of lamps, cauterization by means of red-hot wires, etc.

With regard to the overheating of lamps, although the temperature usually given as the lowest at which ether will ignite is 180° C., ether contaminated with peroxides will ignite at 100° C. This fact was established after an explosion some years ago at Birmingham. Ether vapour is very often found to be contaminated with peroxides. If oxygen is bubbled through ether and the residue is tested at the end of an hour, peroxides are almost invariably found in it. Arrangements should therefore be made for ensuring that the external temperature of surgical lamps does not exceed 100° C.

The second aspect, the ignitable or explosive mixture, has also to be taken into account. As Dr. Hadfield has pointed out, almost every inhalation anaesthetic in use at the present time is explosive or will ignite in anaesthetic proportions of air, oxygen, or nitrous-oxide/oxygen. Almost all the vapours employed in anaesthesia have a greater density than that of air, so that they sink towards the floor, and ignition may be produced at a great distance from the source by means of foot switches and spark-gap interrupters such as those used for diathermy apparatus.

Lastly, there is the question of separating the source of ignition from the explosive mixture. Open-circuit methods of anaesthesia are obviously extremely dangerous from this point of view. Closed-circuit methods are much safer because the anaesthetic mixture is entirely confined and is saturated with water vapour.

Mr. F. C. Raphael: I am interested in the question of what is the penetrability of the explosive mixture, or the travel of the ionization. Considering the ordinary conditions of an operating theatre, with the anaesthetic being applied in the middle of the room, by the operating table, presumably we can take it that the explosive mixture will travel sufficiently into ordinary switches with comparatively loose-fitting covers for a spark on the switch to explode the mixture, or at any rate to start the cold flame which Dr. Townend has demonstrated to us; but what about switches in iron boxes which may be either on the surface of the wall or sunk in the walls? They have covers, but they are not gastight; can we

regard them as safe? Have we to consider whether it is dangerous to use them in adjoining rooms, such as the surgeon's dressing-room and the sterilizing room?

The next point about which I wish to ask is the danger limit of current in the case of a.c. secondaries of head-light transformers. Can we take it that below 30 volts there is no danger if we limit the watts to 70, provided the inductance of the circuit is not abnormally high? This, of course, refers to the secondary circuit only of the stepdown transformer; we must avoid sparks on the switch controlling the primary, and, more important still, we must avoid fizzling sparks whether on the secondary or the primary.

I took up this question of danger from explosion in operating theatres some 4 years ago, about a year before the famous Ministry of Health memorandum was issued. The case in point was a provincial hospital where I was responsible for the electrical equipment, and minor operations were to be done in the anaesthetizing room instead of in the theatre. It seemed to me at once that I must try to get the switches absolutely sparkless. Looking into the matter further, the same argument seemed to apply to the theatre, and it was decided finally that it should also apply to the accident ward. A hand-operated mercury-tube switch was designed for the purpose and was also used in connection with interlocking socket-outlets; these switches are now being used in many hospitals. At this hospital we subsequently met with sparks from the operating table due to static charges. The sparks were attributed to the rubber floor, and to eliminate the trouble I merely recommended the hospital staff to keep the floor damp.

Since then, however, there have been cases of explosion in other hospitals, including two comparatively recent cases in London, in neither of which was the cause of ignition discovered. In one of these every precaution given in the circular of the Ministry of Health had been taken.

(*Communicated*) Something more certain and effectual than endeavouring to keep the atmosphere damp is evidently necessary to exclude the possibility of static sparks. Although tyres and floor coverings of conducting rubber are now available, manufacturers have been finding difficulty in making conducting the thin rubber used for the bladders and tubes of anaesthetic apparatus, and a suitable material is not yet obtainable. I hope that anaesthetists will keep the manufacturers alive to the urgency of this requirement. Surgeons' gloves may present a similar difficulty; but it should be comparatively easy to make conducting goloshes, so that the surgeons need not be put to the indignity of wearing trailing tails, as Dr. Rayner tells us they do in America. If everything else is kept at earth potential by means of conducting rubber, the risk of a charge accumulating due to friction of dry fabrics would not seem to be serious.

Since the danger from sparks from switches and other apparatus in operating theatres became evident, investigations in various hospitals with which I have to do have revealed a number of points calling for attention. Among them I may instance the following:—

A foot-pressure bell switch, used almost immediately under the operating table. To be replaced by an iron-clad tilting mercury-tube switch.

Sterilizers.—In some theatres for minor operations (in which oxygen-ether anaesthetics are also used) there were open-flame gas sterilizers. These have been replaced by electric sterilizers. Electric sterilizers with ordinary series-parallel switches are unsuitable, owing to sparking. Separate tilting mercury-tube switches were substituted for 2-heat control.

Electrically-driven suction pumps for throat, ear, and nose operations.—Gauze guards based on the Davy principle are obtainable, and have been used, but where possible the motor and pump are placed outside the theatre and a suction pipe brought in.

Electrically-driven surgical saws.—These are used at the operating table, frequently with a foot switch and an auto-transformer with open sliding contact. They can be made with squirrel-cage motor and split-phase starter controlled by a special double mercury-tube switch.

Electric cauteries and surgical diathermy.—The use of these must be prohibited when an ether anaesthetic is used.

Pointolite lamps.—Existing designs for spot lights used near the operating table have starting switches mounted on the floor standard carrying the lamp, and draw a big spark at the contacts. The switches are being replaced by double mercury switches.

Ventilating fans.—The fans themselves are probably safe, owing to their positions, even if they are of the commutator type. But the switches should be sparkless or placed outside the theatre. (A sparkless double push-button switch for operating relays was shown at the meeting.)

Key switches on lampholders, laryngoscopes, etc.—These are unnecessary and should be omitted.

Surgeons' head-lamps.—Makeshift flexible connections are only too frequently adopted. The surgeon's head-lamp, however, would almost appear to be an unnecessary survival, since a spot light must surely afford a better means of lighting a cavity when a surgeon is operating.

X-ray apparatus.—I am told by the makers that it is impossible to avoid a spark from the fan used on fan-cooled tubes. Otherwise, shockproof tubes and shockproof cables appear to be safe, and risk from sparking at switches and rheostats within a properly-designed switch table appears to be remote.

In conclusion, I would point out that, since we are already considering precautions to prevent the ignition of ether-oxygen and ether-air mixtures arising from the normal use of anaesthetics, it is desirable that we should not confine these precautions to the close proximity of the operating table. Cases of broken or upset ether bottles have occurred from time to time, and it is preferable to assume that circumstances may arise in which there is risk of ignition and explosion at any point in the theatre within a considerable distance above floor level.

Commander E. L. B. Damant: I should like to support Mr. Swann's suggestion that much of the valuable work described in the papers will be thrown away unless, as a result, some standard is laid down for electromedical equipment which may be used in an explosive atmosphere. I do not feel that a general recommendation on the lines of the Ministry of Health's memorandum

would be as valuable as something in the nature of the Buxton Certificate, whereby a manufacturer could say that he was offering electromedical equipment carrying a guarantee of compliance with safety requirements.

The three phases of work mentioned by Dr. Rayner as needing stringent rules are design, maintenance, and use. As far as use is concerned, surgeons no doubt fully appreciate all the requirements. As to maintenance, the engineer should be able to do what is necessary, with the aid of the memorandum of the Ministry of Health and any further memorandum based upon these two papers. The weak link may be the manufacturer, unless some definite standard is set.

Money is being spent on sparkless switchgear and interlocking sparkless sockets, but it seems doubtful whether inside those closed chambers, usually cast-iron boxes, an explosive vapour is ever present. It would be of interest to know the views of others on this matter.

With regard to small surgical lamps, I think that standardization of voltage should be considered. At present the voltage of these lamps varies widely, and if one is faced with the design of an extra-low-voltage a.c. source of supply in a new theatre it is difficult to know what voltages to provide. The use of alternating current is very convenient, in spite of the advantages of direct current indicated in these papers.

There is one set of figures in Prof. Thornton's paper about which I am not clear. In the Tables showing the maximum permissible current for a given voltage, does the voltage column give the rated voltage of the apparatus only, or the total voltage of supply including the voltage-drop in the recommended ballast resistance?

With regard to air-conditioning, Dr. Rayner mentioned that air-washing can reduce the humidity. Is this an argument against any form of air-conditioning whatever? I should like to know whether, if air-conditioning plant is available which can ensure 58 % to 63 % relative humidity, as recommended in the United States Code, it would be advisable to install it; or whether Dr. Rayner has some objection to all forms of air-conditioning apparatus.

Mr. D. Bulgin (*communicated*): The conducting rubber to which reference is made by Dr. Rayner has been found to be of considerable use in eliminating static charges on vehicles by preventing the generation of a charge at the separation of the tyre surface and road surface since it is impossible for the tyre to acquire a different potential from that of the road surface. There is a point of interest which has been raised by this use concerning the maximum resistance which will dissipate static. A standard tyre made of rubber of specific resistance 10^8 to 10^9 ohms will generate sufficient static to raise the potential of any vehicle to about 5 000 volts at a speed of 10 m.p.h. on a smooth road during warm weather. (In other countries with drier atmospheres the charges are reported to be much higher.) When a tyre of material with specific resistance 1 000 ohms was used no charge could be detected at any speed, but with a tyre of material of specific resistance 20 000 ohms it was possible to detect the generation of intermittent charges at 30 m.p.h. While the speed of separation and the pressures in these experiments were much higher than can occur in hospital practice, they indicate that the rate of generation and the rate of loss of charge, i.e. dynamic charges, are of significance in deciding the maximum permissible resistance. There is little doubt that a resistance of the order of 100 000 ohms would be quite adequate for dissipating static generated by manual operations, but resistances of a higher order than this, while being adequate to earth a surface charge, may give high potential-gradients when dynamic charges are being dealth with.

Conducting rubber has been envisaged for many years, but hitherto it has not been possible to make a conducting rubber without considerable sacrifice of mechanical strength and elasticity, while the conductivity has been very variable. The present material retains all the mechanical properties of high-quality rubber and can be made in any degree of hardness, from ebonite to a somewhat softer material than tyre-tread rubber. The entire range of specific resistance, from pure rubber of 10^{15} ohms to rubber of about 1 ohm, can be obtained, and with few exceptions these resistances can be associated with any required hardness.

The temperature coefficient of resistance of conducting rubber can be varied, and is normally negative at ordinary temperatures. This increases the danger of fire due to electrical leakage, but simple tests indicate that this is negligible with currents of less than 5 mA at ordinary supply voltages (250 volts).

Mr. H. T. Ferrier (*communicated*): In connection with the discussion on these papers, there are two points which I should like to raise:—

(1) How soon can the Dunlop Rubber Co. produce conductive rubber in practical shape and form so far as it concerns the hospitals?

(2) The formation of a "Protection" Committee along the lines suggested by Prof. Russ is long overdue and would be welcomed by hospital authorities just as was the X-ray and Radium Protection Committee.

Prof. C. L. Fortescue (*communicated*): These papers lead me to put forward again a proposal* that I made about two years ago, namely that the time is ripe for the establishment of a close contact between the medical profession and electrical engineers. Electrical science finds many applications in our hospitals and, as these papers and the discussion have shown, the life of the patient as well as that of the hospital staff may well depend upon a small point of purely electrical design. Moreover, alternative methods not at present used may even now be available which would obviate these dangers and perhaps contribute new methods of treatment.

Mr. Swann suggests a liaison committee. I venture to suggest something more than this, something which will enable the whole body of electrical engineering knowledge to be brought to bear on the problems of medical practice. Would it not be possible for the Council of The Institution to have one or two representatives on the Medical Research Council? Or, if the constitution of that body does not permit of this, could not these representatives be members of committees of the Research Council? I would suggest, also, that these representatives of The Institution should have a small committee of electrical engineers on whom they might call for advice from time to time.

* *Journal I.E.E.*, 1936, vol. 78, p. 658.

Mr. G. R. Rimmer (*communicated*): It has been mentioned that when small medical lamps are over-run and finally burn out, they attain a high or dangerous temperature, which might cause an explosion of the gases used. This has not, however, been proved; and in actual tests with these lamps immersed in gas and over-run, no explosion took place.

My point is that if there is a danger of explosion when the lamps are in use, the electric supply to these lamps should be controlled, so that the lamps cannot be dangerously over-run. In other words, there should always be sufficient resistance in the transformers or batteries to prevent the lamps over-running to such an extent that the temperature becomes dangerous when the current is turned full on. If the current is not controlled and something in the nature of a cut-out is introduced, the surgeon will probably experience the trouble of the cut-out working and putting out the lamp during an operation when he decides he requires a little more light. It is therefore more satisfactory to all concerned to have the sources of supply so controlled that the maximum output gives the maximum safe illumination and temperature of the lamp.

[The authors' replies to this discussion will be found on page 169.]

SCOTTISH CENTRE, AT GLASGOW, 8TH MARCH, 1938

Mr. C. H. Wright: To those who are interested in hospital electrical gear and are called upon to provide such gear, collaboration between engineers and medical men must be welcome, and the results of the authors' work provide much wanted guidance.

Electrification can come about in unexpected ways. Many years ago in connection with steam omnibuses we had trouble on occasions due to the vehicle becoming charged, apparently owing to a small leak of superheated steam and the very dry condition of the rubber tyres. A passenger in boarding the 'bus received a shock, and fell (probably in astonishment), a proceeding which had all the chances of being a dangerous one in a busy street. A trailing chain got over this occasional difficulty.

With regard to throat-inspection lamps, we were invited to design a safe and sound unit subsequent to a serious accident in a hospital. We succeeded in doing this, but the apparatus was naturally more costly than the ordinary commercial hand-lamp, and on this account no serious market was found for it. The results of Prof. Thornton's work on the use of a limiting resistance with such battery lamps may enable a less expensive and elaborate unit to be designed. Presumably such a lamp should have either an enclosed mercury-switch or no switch at all. Would the remote event of the mechanical breakage of the bulb of an inspection lamp be necessarily attended with ignition danger?

Now that the authors have thoroughly investigated this matter and given their results we may expect the medical profession to give greater attention to the selection of electrical apparatus.

Prof. Archibald Young: The many risks associated with the use of the various gaseous mixtures employed in operating theatres were first brought to my notice in 1926, during my first visit to America. At that time the American surgeons were full of the subject, and the trouble over there had become so serious that investigations were carried out and measures taken to obviate the risk of explosion in operating theatres.

In one of Dr. Rayner's slides two anaesthetics were shown as non-explosive, chloroform and nitrous oxide. One of these, chloroform, I have been in the habit of using myself, and I still like to use it, even against the advice of some of my colleagues. The great majority of anaesthetic explosions have taken place south of the Tweed, where there has been a prejudice against the use of chloroform. One might almost say that an anaesthetist who uses chloroform in England risks his professional reputation. In my opinion, however, as chloroform is free from risk of explosion we should use it in preference to the newer but more dangerous anaesthetics.

The papers indicate that direct current is less dangerous in the operating theatre than alternating current, and I have had this painfully brought home to me recently, because I am now being forced to change over to alternating current from direct current.

Mr. D. Campbell Suttie: Despite what has been said about chloroform by Prof. Young, I fear we cannot put the clock back in the world of anaesthetics, for I believe that ether is the anaesthetic *par excellence*, although it is dangerous and requires the utmost care in handling. So long as the hospitals employ the younger school of anaesthetists who wish to use these special anaesthetics, and who believe that their use is beneficial to the patients, the hospitals must make provision for their use.

To minimize the risks of explosion, I fear that the only thing to do is to revert to the older practice of installing the instrument sterilizers in the operating theatre, thus providing a good layer of moisture on all apparatus and dissipating possible static charges without producing sparks. It is noted in my own X-ray department that when boxes of films are opened which have been packed in dustless conditioned air, sparks are produced on pealing off the protecting paper; but if these films are left in the moist atmosphere of the dark room for 3–4 days no such sparks can be produced.

I can only hope that by means of a persistently moist atmosphere and the use of conducting rubber the risk of explosion will be removed and that there will be no more fatalities from such causes.

Mr. W. Ross: It has been suggested that the relative humidity of the operating theatre has a bearing on the degree of immunity from electric-discharge explosions. Can Dr. Rayner tell us whether there is any information available which indicates that in districts such as the West of Scotland (where the relative humidity is probably in the neighbourhood of 70 %) or the cotton-spinning districts of Lancashire the risk of accidents due to static electricity is lower than in some other parts of the country?

Mr. John Scott: The question of whether to use chloroform or ether is of paramount importance in

surgical diathermy, particularly with operations involving the throat or mouth, because sparking occurs when contact is made between the flesh and the active electrode. Chloroform is always used for diathermy operations at our hospital, and the risk of explosions is thereby obviated.

Dr. Rayner made reference to the dangers arising from static charges where the patient is lying on a rubber mattress laid on the metal top of a barrow mounted on large rubber wheels. A barrow like this is in use at our hospital, and I have had attached to the metal framework a chain which is allowed to trail on the ground. This barrow is never used in the operating theatres, in view of the risk of an explosion.

THE AUTHORS' REPLIES TO THE DISCUSSIONS

Prof. W. M. Thornton (*in reply*): The impression I have gained from the discussion is that the need for action is urgent, not so much on account of the number of fatalities that have occurred, and are still occurring, as because of the necessity for informing those concerned with surgical operations of the nature of the risks that may arise from certain combinations of the chemical and electrical conditions. Mr. Swann expresses the same conclusion, and I hope that he may be able to convince his medical friends that the time is ripe for combined research.

Dr. Hadfield's opinion that a new anaesthetic gas comparable to cyclopropane but not inflammable is not likely to be found should only, I think, stimulate chemists to find it. With the very complete study of cool-flame combustion and its transition to the more violent explosion given by Dr. Townend, chemists interested in ignition of these vapours know now what to look for and avoid. His explanation of the connection between the spark and hot-wire types of ignition is most interesting and convincing.

I am glad to have Dr. Saunders's results, for it is only by the collection of data from all sides that agreement can be reached. With regard to the working temperature of small surgical lamps, it is necessary to get rid of the heat by radiation or convection, as otherwise filaments and their attachments will soon give way. For this reason a vacuum sheath is not advisable.

Prof. Russ rightly calls attention to the free use of the terms "arc" and "spark" to denote the phenomena at the break of a circuit. "Momentary arcs" is what I have called them elsewhere, but, when one knows what is occurring, "spark" is a more convenient term for common use. From the brightness of these small lamps and the temperatures at which the filaments are run one would have expected higher temperatures than those given in Table A.

The formation of peroxides, mentioned by Dr. Hewer, is most interesting. One would like to know more of their action in the start of cool flames.

Mr. Raphael asks whether a.c. 30-volt circuits will safely carry 70 watts if the circuit is non-inductive. Fig. 5 in my paper would indicate that at 30 volts a current of 1 ampere is the limit, with no factor of safety. With regard to the safety of wall switches, there is, I think, little risk at distances of 10 ft. There is evidence of risk from floor switches, though I have not heard of any cases of ignition produced in that way.

In reply to Commander Damant, the voltages shown in Tables 1 and 2 are the total circuit voltages, and the limiting resistance is the total resistance in the circuit, not the ballast resistance alone.

I fear that Mr. Wright's experience in finding no sale for a thoroughly sound device is not unusual, even when lives are at stake. If an inspection-lamp bulb were to be broken in an ether-oxygen mixture there would be almost certain ignition, but the event must be extremely rare—if any case is on record.

Prof. Young is an advocate of chloroform, and its use turns on the safety it gives in certain classes of operation where thermal ignition of an inflammable mixture would be inevitable. There is no doubt that the use of chloroform entails greater care. One may hope that in time the perfect anaesthetic will be discovered.

Dr. E. H. Rayner (*in reply*): I have prepared a list of anaesthetic gases and vapours (see Table B) with their physical properties and with an indication of the proportion in which they are used for anaesthetic purposes. The number of anaesthetic agents is continually growing, but the great majority are of the solid or liquid form and are safe from an explosive point of view.

The risk which exists when ether is used has been illustrated by the very interesting experiments of Dr. Townend, which demonstrated the "cool flame" method of propagation, a phenomenon described by Davy in 1817, to which I have referred in the first item in the Bibliography (see page 160).

I should like to emphasize one factor as regards ether: it is the only explosive anaesthetic vapour of a density materially greater than that of air. While other anaesthetic gases and vapours, having a density not very different from that of air, will diffuse comparatively rapidly and soon become unignitable, ether vapour is likely to pour downward in a concentrated stream. When it is used with oxygen, it will carry the oxygen with it, increasing the possibility of an ignitable proportion being present. I have no doubt that the heaviness of ether vapour has been a contributory cause in some cases of explosion, one of which I have investigated, especially when actual ignition has been due to electrical equipment producing sparks near floor level.

The subject of the risks associated with electrical switches and their position has been mentioned by various speakers, and the possibility of there being a dangerous layer of ether vapour a few inches deep on the floor indicates that switches and other electric fittings should be placed well above floor level. If they were mounted 3–4 ft. high this element of risk would be largely removed. The use of cord-operated ceiling switches or of relay or contactor switches, operated by a safe low-voltage supply, might be considered for general equipment in operating theatres.

As regards Mr. Swann's remark on the specific resistance of conducting rubber, I have drawn attention to the risk of its value being too low, when the current which would pass at 230 volts would be likely to ignite it,

Table B

THE EXPLOSIVE RANGE OF THE VOLUMETRIC PROPORTION OF GASES AND VAPOURS WHEN MIXED WITH AIR AND OXYGEN*

Heat of combustion (cal. per g. mol.)	Boiling point (°C.)	Formula	Material	Range with air	Range with oxygen	Percentage used with oxygen
660	35	$(C_2H_5)_2O$	Ether	1·8 to 36	2·1 to 82	3 to 15
330	− 102	C_2H_4	Ethylene	2·7 to 28	2·9 to 80	80
530	− 34	C_3H_6	Cyclopropane	2·4 to 10	2·4 to 50	15
330	12	C_2H_5Cl	Ethyl chloride	4 to 15		
110	61	$CHCl_3$	Chloroform	Non-explosive		
(− 19)	− 90	N_2O	Nitrous oxide	Non-explosive		
310	− 84	C_2H_2	Acetylene	3·4 to 50	3·4 to 90	
58	− 260	H_2	Hydrogen	4 to 70		
		..	Petrol	1·5 to 6		

* The values are in parts per 100, in the gaseous state.

and I have suggested that objects should have resistances of 100 000 ohms and upwards. I have shown how samples of rubber of a volume of 1 or 2 cu. in. may become quite warm in a few seconds at this voltage, if the specific resistance is low.

Dr. Hadfield remarks that there seems to be little chance of a gaseous type of anaesthetic being discovered which would be as satisfactory as the best at present available, and would also have the property of non-explosiveness. Perhaps we may hope that, as the mode of action of gaseous anaesthetics is still so much a mystery, there may be some material awaiting discovery or application which will have the desired properties.

The useful information provided by Mr. Raphael indicates the number of subjects needing attention. As regards the position of sterilizing rooms with steam equipment, I have found that practice varies. In one modern operating theatre of a large hospital I have found that the entrance to the sterilizing room from the operating theatre is of about 50 sq. ft. and is without a door, a scheme deliberately adopted in order to provide ease of access and to keep the theatre warm and the air damp. In another large hospital of the latest design the sterilizing apparatus has been isolated from the operating theatre.

Commander Damant states that surgeons fully appreciate the requirements as regards the use of electromedical apparatus. The medical profession cannot be expected to be aware of all the troubles which may occur in electrical equipment. Their tendency is naturally to use it as it is provided for them, and the transgression of the nebulous border-line between use and abuse has been a definite cause of trouble. The aim should be to make plant as foolproof as possible, as in all branches of engineering; and the standardization of equipment as regards small operating lamps seems to me to be one of the more important matters requiring attention. This is emphasized by Mr. Rimmer and other contributors to the discussion. Mr. Bulgin's information concerning conducting rubber is quite useful as showing the order of magnitude of the resistance which may be expected to be effective, agreeing with what I have suggested. I would point out to Mr. Ferrier that I showed at The Institution a sample of an anaesthetic breathing-bag and of the usual type of corrugated face-piece tubing. They were made out of conducting rubber by the Dunlop Rubber Co., and had a resistance between their ends of the order of 1 megohm.

In reply to Mr. Ross and Mr. Scott, I should consider that serious static electrification is more unlikely in Western Scotland than in some other parts of the country. I suggest that simple experiments would show whether trouble might be anticipated. Thus patients' trolleys on rubber wheels may be rubbed with wool, cotton, or rubber material, either directly on the metal top or on a rubber mattress or sheet. The fabrics may be tried in their normal condition and also when well dried, and the operator may be insulated on a rubber mat or "earthed" by leather-soled shoes on a terrazzo floor.

Instrumental equipment for the detection of electrification is hardly necessary. Its presence can be proved by bringing the finger close to the metalwork and trying whether the discharge can be felt. The tyres of the trolley may be sufficiently conducting through the effect of age, etc., to prevent appreciable electrification. Pieces of ebonite or rubber sheeting can be put under them for experiments of this kind, which would be more likely to give a positive result in dry, cold weather.

Earthing chains must be fixed in a good mechanical manner to the metalwork of the equipment to which they are attached. Experience has shown that electrical contact may be defective without this being suspected.

VOLTAGE REGULATION OF THE SIX-PHASE FORK-CONNECTED, GRID-CONTROLLED, MERCURY-ARC RECTIFIER*

By J. HIGHAM, M.Sc., Associate Member, and J. P. WOLFENDEN, M.Sc., Graduate.

(*Paper first received 4th January, and in final form 12th February*, 1938.)

SUMMARY

The paper establishes theoretical formulae for the predetermination of the mean d.c. voltage of a 6-phase grid-controlled mercury-arc rectifier at large ignition angles. The formulae apply to all loads, from the highly inductive to the essentially non-inductive, and include all essential factors. An experimental investigation gives satisfactory evidence of their validity. This fuller theory proves that, strictly speaking, it is incorrect, in non-overlap cases, to allow for arc-drop by arithmetic subtraction. A selection of oscillograms is included which show smaller ignition angles than those generally accepted (*a*) for arc extinction, and (*b*) for the limiting angle between overlap and non-overlap on non-inductive loads.

INTRODUCTION

For given a.c. conditions the voltage obtained on the d.c. side of a controlled mercury-arc rectifier depends upon both the amount of the load and the nature of it, e.g. whether it is almost purely resistive, almost purely inductive, or of a mixed type. For analytical purposes it is convenient to regard the determination of this d.c. voltage as two separate problems, according as the arc from one anode passes on to the next, with or without a period of extinction, or, as it is more usually expressed, without or with "overlap."

These problems were worked out almost to exhaustion in the years 1932 to 1934, and appear in the first six papers listed in the Bibliography at the end of this paper.

The present investigation is concerned with the "non-overlap" case, and is consequently confined to the larger ignition angles and lower output voltages. It differs from its predecessors in the allowance made for arc and resistance drops and in the experimental verification. Also, it is limited to the 6-phase fork-connection of the rectifier transformer, with star-connected primary, and only considers the usual method of grid control, in which the instant of ignition is delayed by an equal amount in all the anodes.† The treatment is applicable to various types of d.c. load, ranging from almost pure inductive reactance to practically pure resistance.‡

(1) THE "OVERLAP" CASE

The voltage vector diagram of the 6-phase fork-connection is shown in Fig. 1, and the corresponding connection diagram in Fig. 2. In Fig. 3 are represented the voltages of the transformer, e_1, e_2, and e_3, between the neutral point N and the three anodes, 1, 2, and 3 (Fig. 1), and the full vertical line is taken as the origin for phase reference. The angle α is the angle of delay in the striking of the arc at anode 2 (the so-called "ignition" angle); "u" is the period of overlap, during which both the anodes 1 and 2 carry current. With sufficient inductance in the d.c. circuit to maintain an essentially constant direct current, the mean ordinate of the shaded area gives the average d.c. voltage.† An approximate solution, taking supply system reactance into account, has recently been published by Kilgore and Cox.‡ With

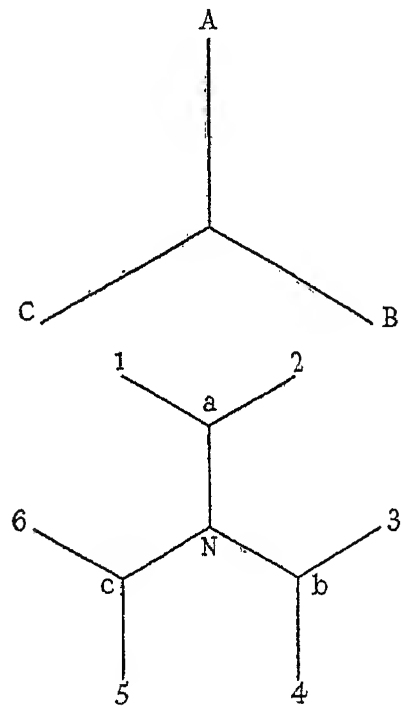


Fig. 1

pure non-inductive loading, on the other hand, where the direct current cannot be assumed constant, we have a somewhat modified and more involved problem, which has been fully treated by Müller-Lübeck and Uhlmann.§

In the case of pure resistance loading, the transition from overlap to no-overlap is generally stated to occur at an ignition angle of 60°, but the small level portions at the lower parts of the oscillogram in Fig. 4 for $\alpha = 60°$ show that the transition has already occurred. This is due to extinction at an anode taking place when the a.c. voltage wave has fallen to a value equal to the then-existing arc drop of the rectifier. The dots on the oscillograms are 10 electrical degrees apart and are produced by the method recently described by Williams and Wolfenden,|| and the two different overlaps on the curve for

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

† See Bibliography, (7).
‡ *Ibid.*, (8).

† See Bibliography, (4).
‡ *Ibid.*, (12).
§ *Ibid.*, (3).
|| *Ibid.*, (9).

$\alpha = 0°$ are due to the different transformer reactances involved in commutating between phases such as 1 and 2, and 2 and 3.*

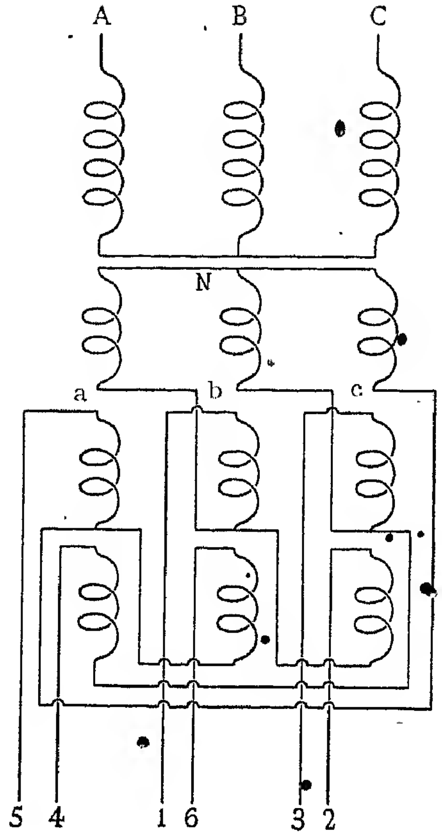


Fig. 2

Integrating, we get

$$i = \frac{E\sqrt{2}}{Z}\cos\left(\theta - \frac{\pi}{6} - \phi\right) - \frac{v}{R} + C\epsilon^{-K\theta}$$

where Z = total impedance of the circuit,

$$\phi = \text{arc tan}\,\frac{X}{R}, \quad K = \frac{R}{X},$$

C = constant of integration,

and ϵ is the base of natural logarithms.

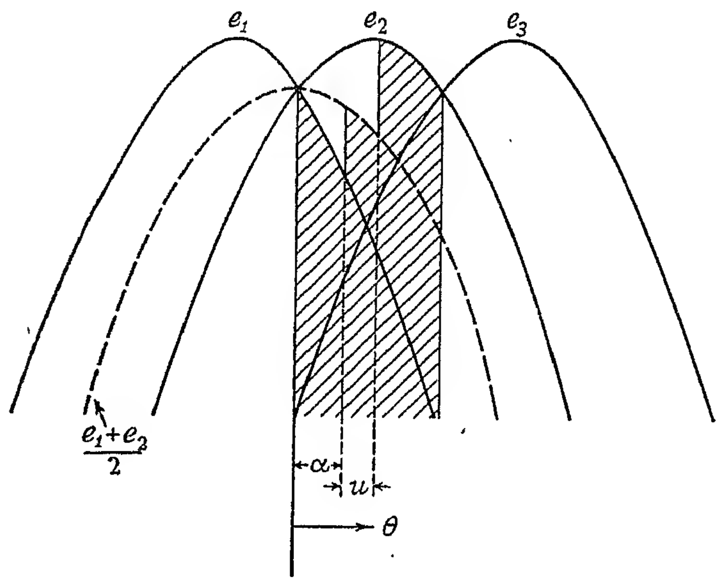


Fig. 3

(2) THE D.C. OUTPUT VOLTAGE EQUATIONS WHEN THE ARC IS EXTINGUISHED DURING COMMUTATION

When the arc has become iguited, say to anode 2, a closed circuit is formed, consisting of the transformer secondary winding N2 (Fig. 1), the load, and the arc.

In the experimental check which follows, X and R were made to include the corresponding primary quantities of the transformer, and E was then the effective secondary voltage to neutral on open-circuit.

When $\theta = \alpha$, and assuming α is so great that no overlap occurs, $i = 0$.

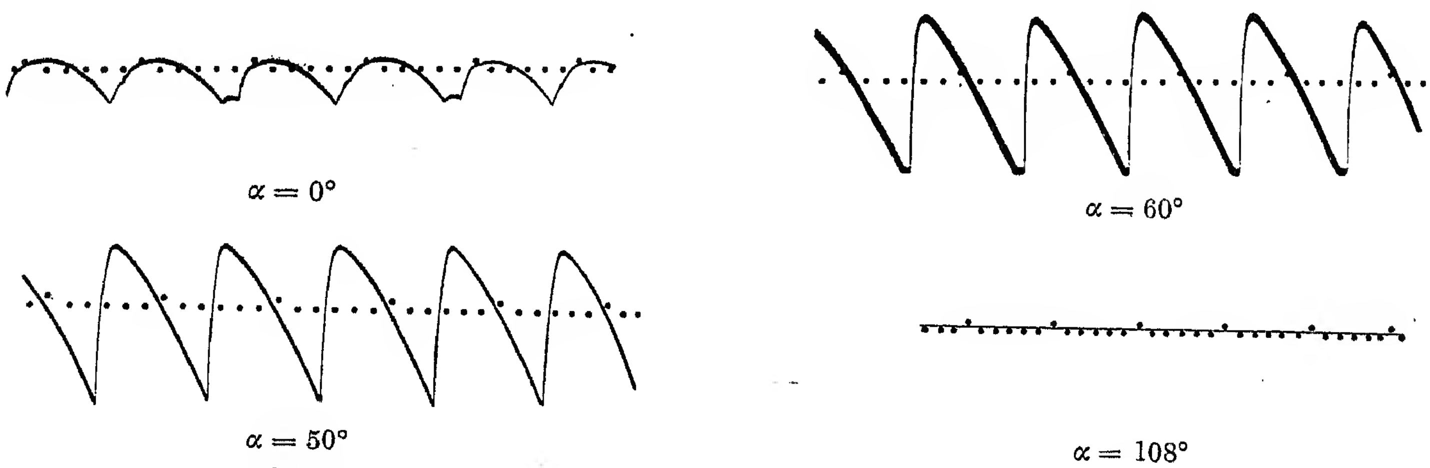


Fig. 4.—Output voltage wave-shapes with pure resistance load.

Applying Kirchhoff's law to this circuit, we have (see Fig. 3)

$$X\frac{di}{d\theta} + Ri + v = E\sqrt{2}\cos\left(\theta - \frac{\pi}{6}\right)$$

where X = total effective reactance of the circuit,

R = total resistance of the circuit and equals $(R_L + R_S)$, where R_L refers to the load and R_S to the transformer secondary,

v = instantaneous value of the arc-drop voltage,

and i = instantaneous value of the current.

* See Bibliography, (10).

Therefore

$$i = \frac{E\sqrt{2}}{Z}\left[\cos\left(\theta - \frac{\pi}{6} - \phi\right) - \epsilon^{K(\alpha-\theta)}\cos\left(\alpha - \frac{\pi}{6} - \phi\right)\right] + \frac{v}{R}\left[\epsilon^{K(\alpha-\theta)} - 1\right] \quad . \quad . \quad . \quad (1)$$

(a) The Case of a Pure Resistance Load.

If the transformer reactance is negligible, then

$$X = 0, \; K = \infty, \text{ and } \phi = 0.$$

Hence equation (1) becomes

$$i = \frac{E\sqrt{2}}{R}\left[\cos\left(\theta - \frac{\pi}{6}\right) - \epsilon^{\infty(\alpha-\theta)}\cos\left(\alpha - \frac{\pi}{6}\right)\right] + \frac{v}{R}\left[\epsilon^{\infty(\alpha-\theta)} - 1\right] \quad . \quad . \quad . \quad (2)$$

Considering values of θ greater than α,

$$i = \frac{E\sqrt{2}}{R}\cos\left(\theta - \frac{\pi}{6}\right) - \frac{v}{R}$$

Now $i = 0$ when $\theta = \alpha$ and when $\theta = \text{arc cos}\,\frac{v}{E\sqrt{2}} + \frac{\pi}{6}$, i.e. when the applied voltage becomes equal to the instantaneous arc drop.

Thus the average d.c. output voltage across the load

$$= \frac{6R_L}{2\pi R}\left[\int_{\alpha}^{\text{arc cos}\frac{v}{E\sqrt{2}}+\frac{\pi}{6}} E\sqrt{2}\cos\left(\theta - \frac{\pi}{6}\right)d\theta - \int_{\alpha}^{\text{arc cos}\frac{v}{E\sqrt{2}}+\frac{\pi}{6}} v\,d\theta\right]$$

$$= \frac{6}{2\pi}\cdot\frac{R_L}{R}\left[E\sqrt{2}\left\{\sqrt{\left(1 - \left(\frac{v}{E\sqrt{2}}\right)^2\right)} - \sin\left(\alpha - \frac{\pi}{6}\right)\right\} - v\left(\text{arc cos}\,\frac{v}{E\sqrt{2}} + \frac{\pi}{6} - \alpha\right)\right] \quad (3)$$

If in equation (3) the arc drop is neglected and $R_L = R$, we get the well-known formula* for the average d.c. output voltage at large ignition angles, namely

$$V_D = \frac{6}{2\pi}E\sqrt{2}\left\{1 - \sin\left(\alpha - \frac{\pi}{6}\right)\right\} \quad . \quad . \quad (3a)$$

The more general equation here derived shows that, strictly speaking, it is incorrect to account for the arc drop by subtracting its average value from the expression (3*a*), although this procedure remains correct at the small ignition angles covered by the "overlap" case. The error in practical cases, however, is likely to be small.

(b) The Case of a Highly-Inductive Load.

If $X >>> R$ so that K is very small, then $\phi = 90°$, and from equation (1) we have

$$i = \frac{E\sqrt{2}}{X}\left[\sin\left(\theta - \frac{\pi}{6}\right) - \sin\left(\alpha - \frac{\pi}{6}\right)\right].$$

Now $i = 0$ when $\theta = \alpha$ and when $\theta = \left(\frac{4\pi}{3} - \alpha\right)$

Thus the average d.c. voltage

$$= \frac{6R_L}{2\pi}\cdot\frac{E\sqrt{2}}{X}\left[\int_{\alpha}^{\frac{4\pi}{3}-\alpha}\sin\left(\theta - \frac{\pi}{6}\right)d\theta - \int_{\alpha}^{\frac{4\pi}{3}-\alpha}\sin\left(\alpha - \frac{\pi}{6}\right)d\theta\right]$$

$$= \frac{R_L}{X}\cdot\frac{6}{2\pi}\cdot E\sqrt{2}\left[2\cos\left(\alpha - \frac{\pi}{6}\right) - \left(\frac{8\pi}{6} - 2\alpha\right)\sin\left(\alpha - \frac{\pi}{6}\right)\right] \quad (4)$$

* See Bibliography, (1).

(c) The Case in which the Load consists of a Mixture of Inductance and Resistance, so that $R = X$.

If $R = X$, then $K = 1$ and $\phi = 45°$.

Then, from equation (1),

$$i = \frac{E\sqrt{2}}{Z}\left[\cos\left(\theta - \frac{\pi}{6} - \frac{\pi}{4}\right) - \epsilon^{\alpha-\theta}\cos\left(\alpha - \frac{\pi}{6} - \frac{\pi}{4}\right)\right] + \frac{v}{R}\left[\epsilon^{\alpha-\theta} - 1\right]$$

Now $i = 0$ when $\theta = \alpha$; also, a value of θ (say $\theta = \beta$) can be found graphically to give $i = 0$ and, integrating between these limits, we find for the d.c. voltage in this case:—

$$\frac{R_L}{Z}\cdot E\sqrt{2}\cdot\frac{6}{2\pi}\left[\sin\left(\beta - \frac{\pi}{6} - \frac{\pi}{4}\right) - \sin\left(\alpha - \frac{\pi}{6} - \frac{\pi}{4}\right) + \left(\epsilon^{(\alpha-\beta)} - 1\right)\cos\left(\alpha - \frac{\pi}{6} - \frac{\pi}{4}\right)\right] - v\frac{R_L}{R}\cdot\frac{6}{2\pi}\left[\epsilon^{(\alpha-\beta)} - 1 + \beta - \alpha\right] \quad (5)$$

This method is directly applicable with any other ratio R to X.

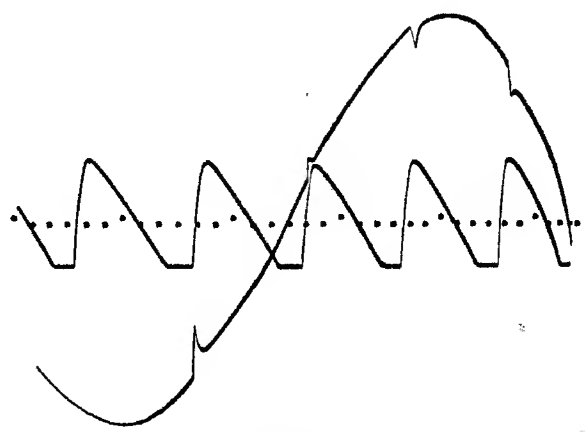


Fig. 5

The critical ignition angle at which the "overlap" case ceases to apply, and after which equations (3), (4), or (5) must be used, depends upon the type of load. In the following verification it was determined oscillographically.

Experimental Check

The only measurements requiring special description are those of ignition-angle and arc-drop.

Ignition Angle.

In this particular rectifier the controlling grids were excited from peaking transformers, which were supplied from an induction regulator.* The regulator was fed from a secondary winding on the main rectifier transformer, and, as a load on the primary of the latter, was negligible. It was found to be necessary in the first place to adjust the ignition instants of the anodes with respect to each other, in order that the period between the ignition of adjacent anodes should correspond to 60 electrical degrees. This was done by means of adjustable resistors inserted in series with the primaries of the peaking transformers.

* See Bibliography, (11).

To facilitate measurement of the ignition angle of the arc when performing regulation tests, the induction regulator, which supplied the grid excitation, was calibrated so that the angle could be read directly on a circular ring attached to the rotor. This was done oscillographically by superposing an oscillogram of the output voltage upon that of the transformer secondary voltage. An example of an oscillogram taken for this purpose is shown in Fig. 5, in which the ignition point is at the right-hand end of the short horizontal strip below the last kink in the anode curve. The distance between this and the upward crossing of the anode curve, minus 60°, is the required ignition angle. The regulator was calibrated by means of a number of oscillograms of this type.

In order that the vertical portion of the grid potential wave should control the instant of arc ignition, a suitable negative grid-bias voltage was applied to the controlling grids. This bias voltage was supplied from a high-tension battery and was oscillographically determined to be 200 volts in the present case.

Arc-Drop.

As the instantaneous arc drop varied during the tests between, approximately, 15 and 30 volts, it was necessary to determine it for each point at which the theoretical equations were to be checked. This was done as shown in Fig. 6, in which a sinusoidal calibrating voltage of known value is superposed upon an anode-cathode oscillogram. The particular anode used is conducting during the more or less horizontal period of the curve, and the distance between this, at any point, and the mean line of the curve (dotted) exceeds the instantaneous arc drop by the reading of a d.c. voltmeter connected across the terminals of the cathode-ray oscillograph. This d.c. correction is due to the self-centring action of the oscillograph when connections to the plates are made through condensers, with the consequent elimination of the d.c. displacement of the wave. With balanced deflection it had previously been shown experimentally that over the working range, and within the permissible limits of experimental error, the Y-deflection of the oscillograph was proportional to the applied voltage. The values of arc-drop were obtained from projected enlargements of the photographic plates on a background of squared paper.

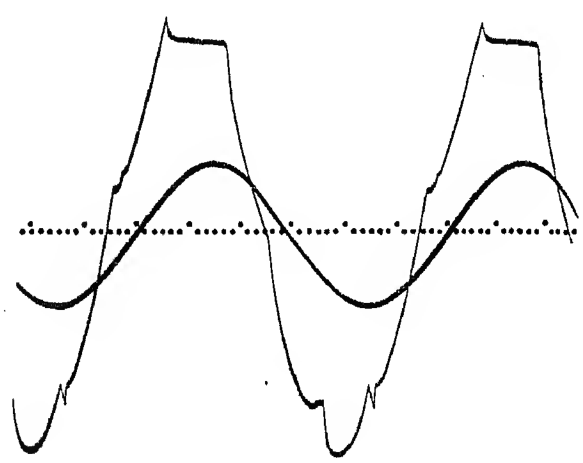


Fig. 6

Voltage-Regulation Tests.

The tests were carried out on a 6-phase, fork-connected rectifier of 2 kW capacity, the primary side of the transformer being star-connected to 3-phase 50-cycle mains.

In performing the first regulation test the sinusoidal input voltage on the primary side of the rectifier transformer was maintained constant and negligibly small distortion of the supply wave was observed. The almost pure resistance constituting the load on the output side was unaltered during the test. At successive ignition angles of 10° from $\alpha = 60°$, the d.c. output voltages were recorded, until the arc became totally extinguished. As the direct current taken from the rectifier altered in sympathy with the d.c. voltage during this test, it was necessary, on altering the ignition angle, to allow time for the rectifier voltage to become steady. The ignition angle was read on the calibrated ring of the induction regulator, and the arc-drop voltage was measured oscillographically at each point, as described above.

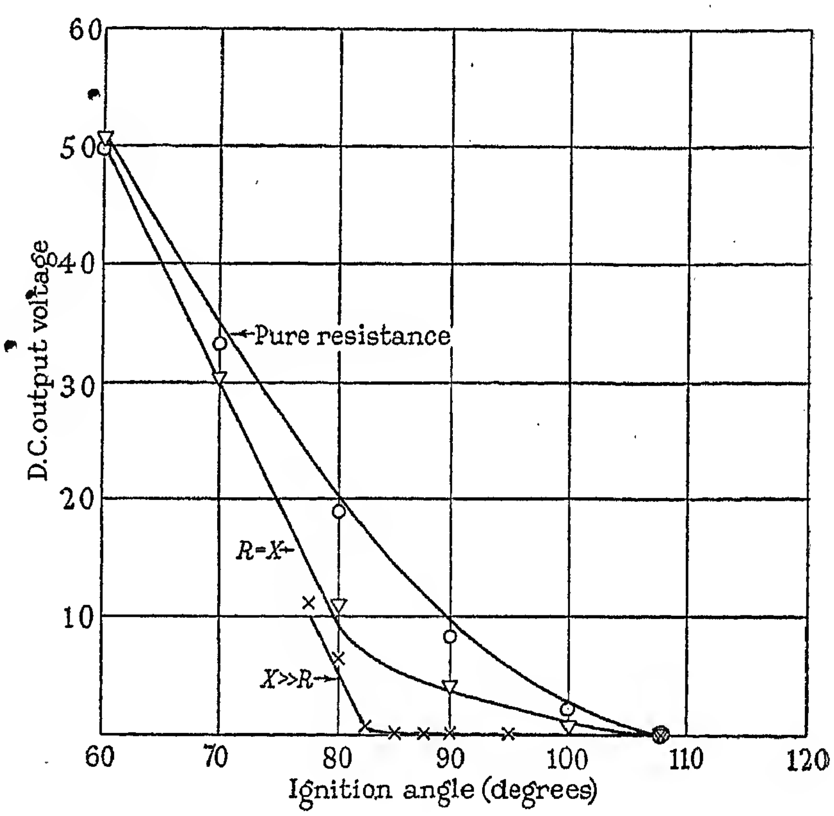


Fig. 7

The full lines are theoretically determined.
The points are plotted from the experimental readings.

The results are exhibited graphically in Fig. 7, in which the top curve is derived from equation (3), and the circle centres are experimental readings of the d.c. voltage for the nearest practicable approach to a non-inductive circuit. Fig. 4 shows that the arc ceases to overlap at an ignition angle less than $\alpha = 60°$ as characterized by the short horizontal portions of the oscillogram for which $\alpha = 60°$. Also, it will be seen that the output voltage attains zero value when $\alpha = 108°$ (Figs. 4 and 7) and not 120°, as is generally stated, for a 6-phase rectifier. Extinction takes place when the available a.c. voltage falls to the value of the then-existing arc drop.

The voltage-regulation test was repeated while the rectifier was supplying a fixed load composed equally of reactance and resistance. The extinction point, as shown by voltmeter, by output-voltage oscillograms, and by the

vanishing of the glow in the arms of the tube, again occurred at an angle of 108°.

The test was repeated with the rectifier supplying a fixed, highly inductive load. Owing to the fact that a load was chosen composed of a very small proportion of resistance, so that X was much greater than R, it was not possible to operate the rectifier at an ignition angle less than 77·5°, because of the excessive current which would have been delivered to the load. It is seen in Fig. 7 that after an ignition angle of about 82° the d.c. output voltage becomes very small. The extinction angle was 108°.

Oscillograms of the output-voltage wave-shape (not reproduced) showed that the two left-hand points on the centre curve (Fig. 7) and the three left-hand points on the bottom curve, were "overlap" points, and their theoretical values were determined by the use of Herskind's inductive-load formula.*

CONCLUSIONS

These are as stated in the Summary. The principles are applicable to rectifiers in which the number of anodes differs from the case here considered, and the theory can readily be modified to meet the change.

Acknowledgment

The work was carried out in the Electrotechnical Laboratories of Manchester University, and the authors are indebted to Prof. R. Beattie, D.Sc., for the facilities placed at their disposal.

* See Bibliography, (4).

BIBLIOGRAPHY

(1) M. DEMONTVIGNIER: "Theory of the Grid-Controlled Rectifier," *Revue Générale de l'Électricité*, 1932, vol. 32, pp. 625 and 659.

(2) W. DALLENBACH: "Current and Voltage Relations of the Grid-Controlled Rectifier," *Elektrotechnische Zeitschrift*, 1932, vol. 53, p. 1059.

(3) K. MÜLLER-LÜBECK and E. UHLMANN: "Current and Voltage Relations of the Grid-controlled Rectifier," *Archiv für Elektrotechnik*, 1933, vol. 27, p. 347.

(4) C. C. HERSKIND: "Grid-controlled Mercury-Arc Rectifiers and Inverters," *Transactions of the American I.E.E.*, 1934, vol. 53, p. 926.

(5) D. JOURNEAUX: "Voltage Control of Mercury-Arc Rectifiers," *ibid.*, 1934, vol. 53, p. 976.

(6) F. O. STEBBINS and C. W. FRICK: "Output Wave-shape of Controlled Rectifiers," *Electrical Engineering*, 1934, vol. 53, p. 1259.

(7) E. ROTH: "Asymmetric Control of Anode Ignition in Mercury-Arc Rectifiers," *Bulletin*, Association Suisse des Électriciens, 1936, vol. 27, p. 704.

(8) H. KLEMPERER and K. STROBL: "Grid-controlled Rectifier with Capacitative Load," *Archiv für Elektrotechnik*, 1933, vol. 27, p. 485.

(9) F. C. WILLIAMS and J. P. WOLFENDEN: "The Time Sweep of a Cathode-Ray Oscillograph. Calibration using a Valve Time-Base," *Wireless Engineer*, 1937, vol. 14, p. 315.

(10) O. K. MARTI and H. WINOGRAD: "Mercury-Arc Power Rectifiers," 1930, p. 150.

(11) H. RISSIK: "Mercury-Arc Current Convertors," 1935, p. 164.

(12) L. A. KILGORE and J. H. COX: "Regulation of Grid-Controlled Rectifiers," *Electrical Engineering*, 1937, vol. 56, p. 1134.

HIGH-POWER VALVES: CONSTRUCTION, TESTING, AND OPERATION

By J. BELL, B.Sc., J. W. DAVIES, and B. S. GOSSLING, M.A.

[Communication from the Research and Engineering Staffs of the M.O. Valve Co., Ltd., at the Works, Hammersmith, and (G.E.C.) Research Laboratories, Wembley.]

(*Paper first received* 20*th January, and in final form* 12*th February*, 1938; *read before the* WIRELESS SECTION 30*th March*, 1938.)

SUMMARY

In the Introduction the authors discuss how the development of high-power valves is influenced by the standard of reliability demanded by such services as broadcasting.

The principles governing the constructional design of each main part of the valve are outlined; differential expansion frequently appears as a controlling factor.

The glass-work is of lead-potash-soda glass, the anodes of thick copper tubing; for glass-to-metal seals nickel-iron alloy is preferred, but copper is sometimes used.

Insulating members have been eliminated from the active part of the valve. Grids are not cross-braced, grid seals include a large ring section let into the bulb, and there is an 8-lead multiple seal for pentodes.

Cathode seals for 1 000 amperes are described; these support the whole cathode system, the evolution of which into a free-hanging multiple construction is outlined. Heat transfer between anode and cooling liquid is discussed, and also forced-air cooling.

Modern evacuation technique proves to be governed by two effects; the lower readings of grid current in the "gas test" are shown to be due to photo-electric electron emission caused by X-rays from the anode and not directly to gas, and the clean-up capability of the valve is found to be very large.

The method is described for determining the operating filament voltage for a standard emission by extrapolation to full emission from a reduced-emission test. Examination of the statistics of emission-test data shows that former variations are to be ascribed to variable thermal emissivity and not to variable dimensions.

Methods are given for extrapolating low-power space-current readings into the operating region, with allowance for division between anode and grid, and the "tail" of the anode-current characteristic is discussed. The control of the secondary-emission component of the grid current and the effect of the magnetic field of the filament are described.

An account is given of later experiments and of recent experience with flash-arc breakdowns (Rocky Point effect).

Recommendations are made for switching-on filaments and anode potential in operation, and for purity of cooling water.

Curves are shown of the distribution of evaporation wastage in various types of filament. Typical valve-life data from normal operation are illustrated by survivor curves for constant voltage and for constant emission during life, and a Table is given showing the recent performance of the largest valves at three stations.

A table of ratings for the various types of valve covered by the paper is also included.

INTRODUCTION

The development of high-power valves is a relatively slow process, so that it is only at intervals of several years that advances can be recorded in any comprehensive fashion. It is actually some 10 years since valves of the particular sort here considered—those made by the M.O. Valve Co.—were described to this Institution by W. J. Picken.* This slowness seems in retrospect to have been imposed by the circumstances in which the majority of such valves are used.

For a better understanding of these circumstances the following instances may be cited.

First of all there is the very high standard of reliability demanded by those services of which broadcasting is the type. In these there is no answering-back or possibility of repetition, and a brief interruption may affect irrevocably a million listeners instead of merely a few. The standard is comparable with that of power-supply plant, for although there are admittedly frequent opportunities for servicing in the intervals of programmes, there is on the other hand no automatic alternative source of supply, even temporarily. It is not the fact that a valve has failed and has to be replaced that is important; it is that an interruption to the service has occurred. It is a question of operation, not of economics. As a result of this requirement, improvements which may affect performance in operation are generally introduced one at a time, leaving well alone for the time being in other directions. Certain kinds of improvement, e.g. in mechanical construction or characteristics, have latterly been accelerated by preliminary studies, using demountable models.

Then there is the long life expected of the valves. This is not the same thing as reliability, for reliability depends chiefly on the absence of premature failures, whereas a long average life has virtues of its own. Apart from the cost of the valves themselves, there would be additional calls on the time of the station staff, and need for more spares at remote stations, if replacements were more frequent. This long life fixes the time unit of the development process at 3 or 4 years, since that is the period generally required to work through the whole of even the first batch of a new type of valve, and so to obtain a first general idea of its overall performance, although the proportion of premature failures, if any, will already have been known after the first few months. Extended life tests of valves of the highest order of power are not feasible, although from time to time manufacturers have recorded their thanks to various authorities for facilities for preliminary operation, which have been of great value in eliminating causes of premature failure. Fortunately, premature failures have been less common in recent types of valve.

Further, none of these large valves are made in very

* See Reference (1).

Plate 1

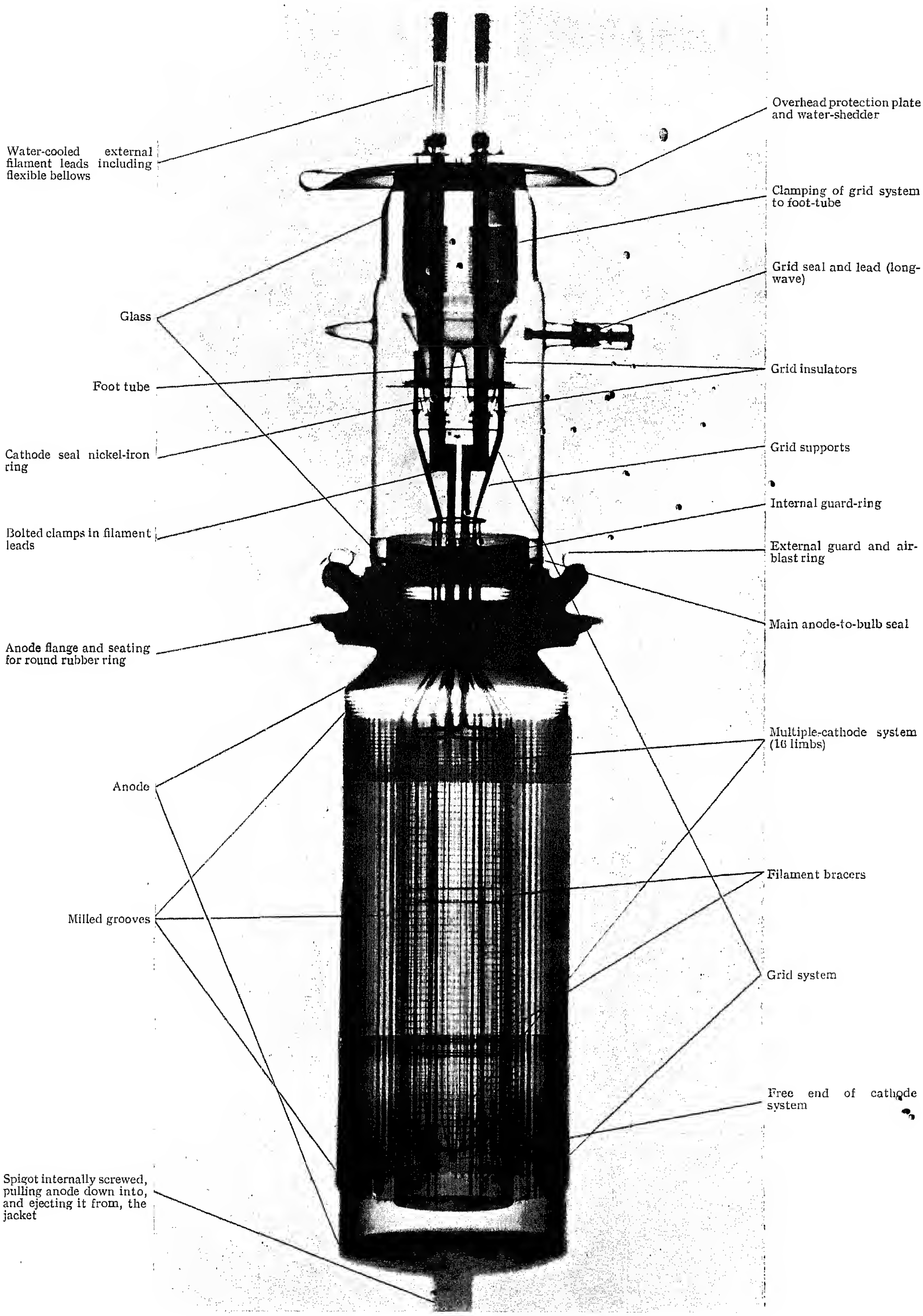


Fig. 1.—Radiograph of a typical high-power valve (type C.A.T.14). Approximately one-fifth actual size.

Plate 2

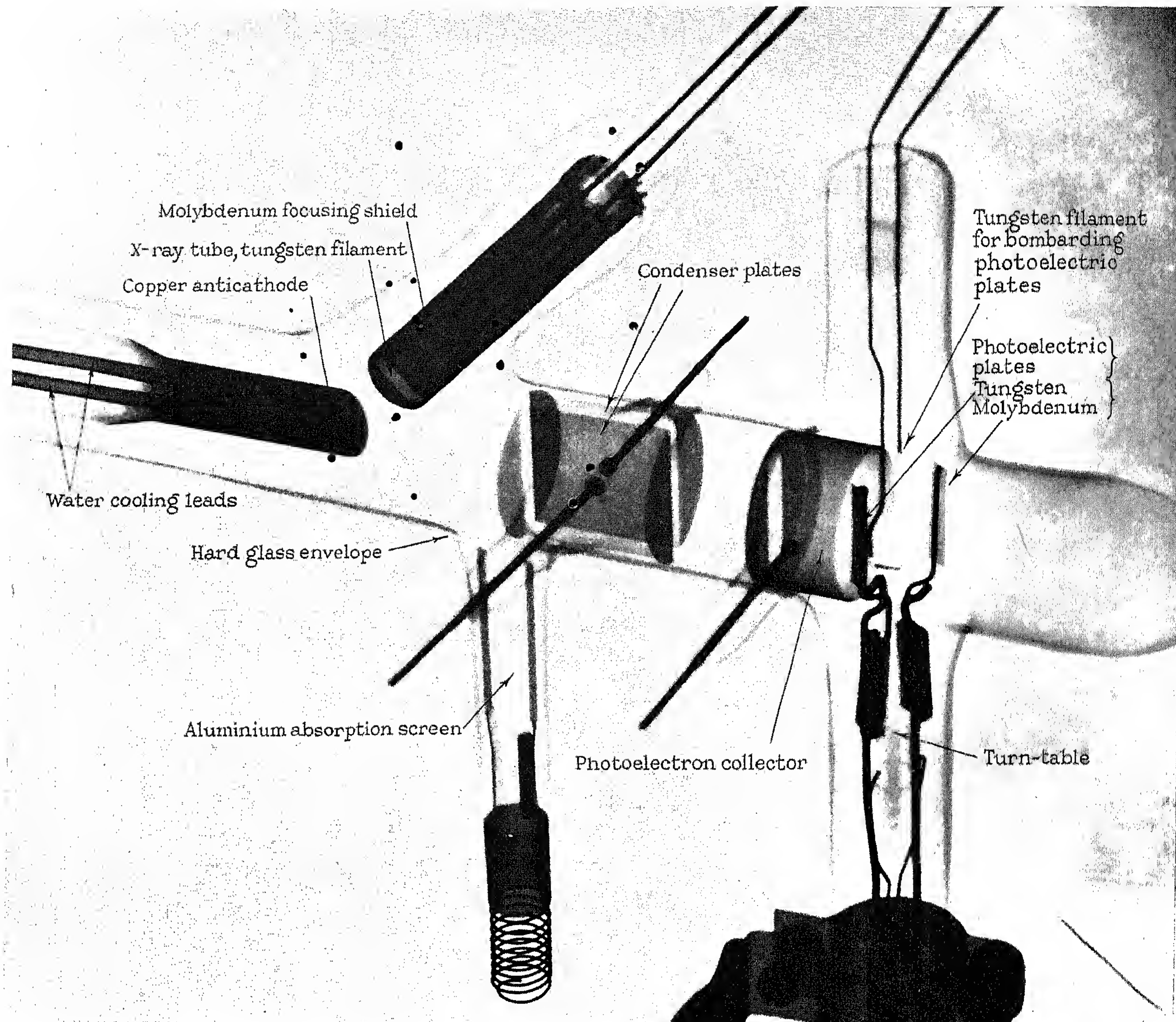


Fig. 3.—Radiograph of the apparatus used to study the photo-electric emission of electrons from tungsten and molybdenum under the action of X-rays from copper.

large numbers, so that the picture of overall performance must be statistically crude if there are many points of difference between different types.

Now these operating conditions and requirements which have been enumerated are much the same for all the many types of valve which come within the scope of this paper. In consequence, there are various threads of common practice running through all the several designs, and it is our purpose rather to follow these threads, giving particular instances in illustration, than to go into detailed description of the few types for which space would permit such treatment.*

To economize space by avoiding repetition, the reader is referred from time to time to a general survey of the development of large radio transmitting valves by Le Rossignol and Hall.†

CONSTRUCTIONAL PRINCIPLES

(a) General

The use made of engineering principles in the construction of small valves is largely concealed because these principles are mainly applied to the machines and tools by means of which the valves are made, and they therefore appear only indirectly in the finished valve. A high-power valve, on the other hand, shows itself more directly as an engineering construction. The principles followed are, however, distinctly specialized and must be classed as an extreme case of what may be called high-temperature engineering.

This is for the reason that in many of the parts of the valves the ranges of temperature experienced between idle and operating conditions are wide, and in some cases very wide indeed. Also, under the temporarily more severe conditions of manufacture, they are in general wider still; in fact, they include the widest at present known in engineering.

These temperature ranges imply corresponding expansions, and our experience with these valves has shown that the one overriding rule which must never be violated, if trouble is not to follow, is that the effects of differential expansion must on no account be ignored.

The valve is, of course, also an evacuated high-voltage device, but the requirements arising in these directions have been found to be of relatively minor importance as regards the constructional design.

Throughout the account now to be given, the demands of differential expansion can be seen in the background of the design, whatever part of the valve may be under immediate consideration.

Fig. 1 (see Plate 1, facing page 176) is a radiograph showing the internal and external construction of a high-power valve, type C.A.T.14; most of the features now to be discussed are indicated in the Figure.

(b) Glass

The glass envelope or bulb is a convenient starting point for this outline of the principles of construction, because in one way or another all the other parts are mounted upon it.

Throughout the development of high-power valves we have continued to use a relatively soft glass. This has served us so well that there has been little incentive to change it, and no change at all has in fact been made. The glass contains a fairly high proportion (30 %) of lead, and in consequence it is elastic and withstands " thermal shock," i.e. sudden local expansion, relatively well; it is also viscous over a rather wide range of temperature, does not de-vitrify quickly through chemical instability, and can be fully annealed at a convenient temperature. Further, joints between glass and glass are in no danger of minute pin-hole leaks. These properties form a good basis for somewhat ambitious glass-working operations, such as main glass-to-glass seals 5 in. in mean diameter.

Troubles which might arise from electrolysis of hot glass parts have been avoided by substituting potassium for half of the sodium and by adding lead. The proportion of lead is sufficient to absorb X-rays to a useful extent, particularly where, as in these valves, such rays strike glass 2 or 3 mm. thick at glancing incidence. The radiograph, taken at 150 kV peak voltage, illustrates this point.

The presence of lead and the low sodium content reduce the high-frequency power factor to a low value, but no use is actually made of this virtue.

The lower softening temperature and higher expansion of this glass as compared with harder glasses of the boro-silicate type are fortunately compensated for by the fact that it absorbs much less low-temperature thermal radiation than those glasses, and is therefore subjected to smaller ranges of temperature during operation of the valves.

The thermal expansion, 9·1 parts per million per deg. C., is probably too great for constructions involving stout metallic members embedded in thick pieces of glass. However, when the very different elastic properties of metals and glasses in general are taken into consideration, such constructions, whatever appearance of robustness they may present, inspire anxiety rather than confidence, and an anxiety which is renewed with every increase of size.

(c) Anodes

The material of the anodes is copper of good ordinary quality with a low content of volatile impurities such as arsenic. In the larger valves the anodes are 5 in. in diameter and $\frac{3}{16}$ in. thick, or 8 in. by $\frac{5}{16}$ in., these latter being milled to a depth of $\frac{1}{8}$ in. in longitudinal grooves $\frac{1}{8}$ in. wide so as to double the surface presented to the cooling fluid. To prevent fine leaks exposure of the " end-grain " of the drawn or rolled metal is avoided. Leaks through the copper are very rare.

For soldering the end plates and alloy rings, high-quality silver solder free from volatile impurities is used. Actually, there was more trouble in times long past in making sound vacuum-tight joints between copper and alloy than between alloy and glass; it was found essential to distribute the strains due to differential thermal contraction fairly between the two materials.

It is sometimes found worth while to blacken parts of the inside of anodes with graphite, in order to reduce the furnace effect of the intense cathode radiation and the proportion of such radiation reaching the glass envelope.

* A table showing the principal ratings for the various types of valve mentioned in the paper and for the other high-power types is given at the end of the paper.
† See Reference (2).

These large anodes expand to a notable extent when heated. For a 21-in. length the expansion at the "baking temperature" of 400° C. is 0·14 in., and at the full-load operating temperature of about 130° C. 0·034 in. This latter expansion can be met by using rubber rings of circular section between anode and jacket, but *not* by flat rubber gaskets.

The cooling of anodes will be considered later in this Section.

An internal guard-ring overlapping the seal is inserted into the throat of the anode for the purposes of protecting the seal and the neighbouring part of the glass from cathode radiation, metallic deposits, strong electric fields, and damage from discharges, or electrolysis consequent on direct electron bombardment.

(d) Glass-to-metal seals

The seal between anode and bulb is the most striking in point of size, but, as we shall see, the same principles apply to the other seals.

Wherever possible a ring of nickel-iron alloy whose expansion is closely matched to that of the glass is interposed between glass and copper. This ring is usually copper-plated, and treated with borax to improve adhesion to the glass. The correctness of the composition of batches of alloy is carefully watched, and all batches are checked for expansion. Given this control, the actual sealing edge need not be thinner than can readily be obtained by simple turning—and the alloy machines quite well—and it can be left with ample strength to resist the atmospheric thrust which for a seal of $5\frac{1}{4}$ in. diameter amounts to 20 lb. per inch of circumference, i.e. more than 300 lb. in all.

The reliability of these seals is unquestionable; failures, whether during manufacture of the valves or afterwards, are extremely rare—a result well worth the few additional operations they require.

Since the glass is applied to the outside only, protection from indentation of the alloy ring is provided in the finished valve. Otherwise there is only one likely cause of fracture. This should be mentioned because it might not be expected. A clean crack round the body of the glass clear of the seal itself can result from a sharp blow on the anode or its supports due, for instance, to sudden contact with a hard object. A similar blow on the glass does not produce this effect.

In cases where the seal is in a strong high-frequency magnetic field which can induce toroidal eddy-currents in it the bare nickel-iron alloy is unsuitable; it overheats to a remarkable degree. To avoid this, either the nickel-iron is copper-plated thickly enough to survive oxidation when the seal is made, or else a direct copper-to-glass seal is substituted. The latter is successfully used up to $5\frac{1}{4}$ in. diameter; it requires close control of the sharpness of the edge combined with sufficient thickness to withstand the atmospheric thrust even when the copper is fully annealed; the glass is usually applied to the inside only.

After experience of both types the ring of intermediate alloy is still preferred wherever there is free choice, except perhaps in small sizes less than $\frac{3}{4}$ in. diameter.

(e) Insulation

The glass envelope itself is the main insulator, but its insulating properties call for little comment. On the outside it is warm and dry, and high-voltage breakdown would occur first in the heated air. The only danger point for electrolytic conduction would be between the filament seals, particularly if a.c. heating is used, but there the temperature is kept low for the sake of the seals themselves.

However, those parts which are subject to high-frequency electric fields can be destructively overheated if their surfaces on the vacuum side are coated, even discontinuously, with a conducting film whose resistance is of the same order as the capacitative impedance of the space round about the film. Since the heating results from the diversion to the film of the displacement current in the space, this effect is more troublesome in short-wave valves. The formation of such films by volatilization or sputtering of internal metal surfaces during exhaust has therefore to be avoided. High-frequency dielectric losses in the glass itself are completely negligible in comparison with those in such films. The internal guard-ring extension of the anode prevents the formation of films in the stray field close to the anode seal.

Of other insulators besides the envelope there are hardly any. Their presence within the active portion of the valve is nowadays in no circumstances permitted. The combination of some or all of the adverse agencies of high temperature, high voltage, and high frequency, together with film formation, is altogether too hard on them for good reliability to be expected. There is a further less obvious probability which our experience has sufficiently demonstrated in those cases where we have tried to use steadying insulators in such places. This is, that any breakdown of films will result in much more serious breakdown of the vacuum insulation through piloting of flash-arcs—assisted Rocky Point effect.*

The grid-cathode insulators, which, if used, are of silica and similar in form to those of ordinary sparking plugs, are therefore withdrawn to a position as far as possible from the active regions, and the cathode system is insulated solely at the seals.

(f) Grids

The main constructional problem in grid-building is differential expansion. Owing to differences both in the thermal capacity of different parts, and in their rates of heating by radiation and bombardment, this sets up strains leading to progressive distortion, unless the structure is so designed as to avoid such strains. For this reason, diagonally-braced grids were early given up and an adequate, though reduced, rigidity was provided by thickening the longitudinal members.

If the μ of the valve is to be low, the grid consists simply of parallel rods; for higher values of μ a spiral of suitable pitch and thickness is added, secured by lacing spirals or, more recently, by welding. Grids in high-power valves are at present made wholly of molybdenum. The possibility of substituting tungsten for the purpose of reducing primary thermionic emission from portions overheated by radiation or bombardment has so far been held in reserve.

* GOSSLING, see Reference (3).

(g) Grid seals

In the largest short-wave valves, e.g. C.A.T.17, the grid seals have to have a large high-frequency current rating of 100 amperes or so in normal operation, and also a considerable margin to cover mistuning of the load and local concentration of high-frequency current. The construction of the seal has therefore to be so substantial that it may as well be used for insulation and support; in these types it therefore consists of a metal ring separating two parts of the bulb with a glass-to-metal seal on either side. These are the large $5\frac{1}{4}$-in. copper-to-glass seals already mentioned; copper-plated nickel-iron is also used.

When separate seals are used, the difficulty of so disposing the external conductors as to ensure equal distribution of high-frequency current restricts to two the number of seals which can usefully be considered. Given equal distribution, the inductance of the grid leads is of course halved. These separate seals are made like miniature anode seals, and direct copper-to-glass joints are now usually used, since their special troubles are least at the sizes required, whereas nickel-iron seals have to be copper-plated, and can be troublesome if too small.

Even in long-wave valves, grid seals of good high-frequency current rating have to be provided as a safeguard against emergencies arising from parasitic short-wave currents.

For the highest-power valves of the multiple-electrode class, such as pentodes, it has been found possible to mount a ring-cluster of separate seals in the foot-tube. A pair of seals at opposite ends of a diameter is provided for each internal electrode, so as to halve the inductance, which is further reduced by keeping all seals short. For the assembly of these clusters special glass-blowing appliances and technique have been developed.

Another possible form of grid seal, not yet extended to the largest valves, is the multiple-wire seal used in some of the smaller short-wave and ultra-short-wave types. This consists of as many wires as may be desired set in a ring, and passing either through the main glass-to-glass seal between bulb and foot-tube, or through a circular " pinch " on the foot-tube itself.

This sort of seal has been found to give a very good combination of high current-rating, and low grid-lead inductance, in consequence of which the types in which it is used have given lower wavelength limits, and better performance in that neighbourhood than were anticipated.

(h) Cathode seals and mountings

The cathode seals in large valves have nowadays to carry heating currents of up to 700 amperes in operation, and considerably more during exhaust. In addition, the elimination of all internal insulators between the cathode and other electrodes requires that these seals should be strong enough to carry the whole weight of the cathode system, that is up to $1\frac{1}{4}$ lb., with the centre of gravity 24 in. from the seal. A satisfactory solution of this double problem has been found in the use of a seal which is a miniature replica of the well-tried anode-to-bulb seal. The smallest of these used is $\frac{1}{2}$ in. in diameter for 250 amperes. There has been no difficulty with progressive increase in size; the largest so far have a diameter of $1\frac{1}{4}$ in. for 1 000 amperes or more.

For sealing to the two tubular extensions provided on the main foot-tube, the two seals are mounted on a common jig of nickel-iron, which has a spring grip to prevent temporary strain in the seal when the glass is setting. The stout copper extensions of the seals on the vacuum side have accurately-machined faces, to which the internal leads supporting the cathode system can be bolted in good alignment without further adjustment. It should be mentioned here that electrical contact between clamped metal surfaces is much better in vacuum than in air. In general it can be said that these seals behave as well as they do, because the design implies a fair division of responsibility between the mechanic and the glass-blower.

A further important but not so obvious function of the cathode seals and external leads is to remove the heat conducted back from the incandescent cathode, and also that generated by ohmic heating of the internal leads, which are designed as a compromise between these two effects. The total power to be dissipated amounts to 150 watts in each 700-ampere seal. There are two alternative methods in use, the first used was liquid cooling of the hollow external leads down to the point where they are screwed into the seal. The screw, incidentally, is greased to preserve the contact. The leads have to be provided with flexible centre sections of corrugated metal tubing in order to reduce strains on the seal, and in some of the earlier large valves water-leakage troubles have developed, usually after some 5 000 to 9 000 hours, through corrosion, possibly electrolytic, of these flexible " bellows." With the silver bellows more recently used this is unlikely. The other alternative, which is in several ways more convenient, particularly when the cathode is not at earth potential, is to substitute cooling by forced air-blast. With leads having fins machined on their inner ends, and air supply at 4 in. level of water pressure, this method seems quite satisfactory.

(j) Cathodes

We now come to the innermost component of the valves, the cathode system. The final form of this, simple though it is, is yet the product of a long evolution, in course of which the essential principles were successively appreciated.

To obtain an emission current of 165 amperes, which is the largest so far demanded, with a working life of the order of 10 000 hours, a total area of some 50 sq. in. (300 cm^2) of incandescent tungsten has to be provided. This takes the form of an assemblage of filaments of diameter 1·15 mm., requiring some 22 kW to heat them, and all mounted with a constant separation of 9 mm. from the adjacent wires of the grid.

The principal mechanical factors governing the design of these multiple-cathode systems are the unavoidable facts that in coming up to incandescence the longitudinal expansion of the filaments themselves is 1·2 %, i.e. 4 mm. on a length of 350 mm., and that the lateral magnetic forces between the individual currents of 60 amperes or so tending to distort the system are by no means negligible, and are considerably greater than the electrostatic forces acting on the system when the emission is cut off or otherwise not space-charge limited. For dealing with the expansion, sliding guides are best avoided, especially if

the sliding surfaces are at anything near red heat, because of the strong tendency of metallic surfaces to weld together under such conditions. If one of the surfaces is vitreous or ceramic, this tendency is probably less, but as we have seen, internal insulating bodies are avoided for other reasons. Further, friction between surfaces in vacuum is greatly increased, probably by the removal of gas films.

For these reasons less and less use has been made of such guides in the progressive evolution of cathode systems, until they have finally been eliminated altogether, leaving a free-hanging system supported only on its seals. That a good standard of reliability is achieved by the use of such systems has now been proved in service by several years' operation of valves of the largest size, and by the similar good behaviour of their immediate predecessors.

Their immediately obvious disadvantages of relative lack of rigidity and of apparent relative fragility were of course borne in mind from the first, but the event has shown that these were by no means so serious as might have been feared.

The resultant magnetic force between the current in one limb of the system and those in its fellow limbs depends on the method of connection of the limbs. This may be exemplified by a brief description of various types of cathode system which have been used. Currents and voltages will be quoted in round figures. In the earlier types up to C.A.T.5 there were two 10-volt loops carrying 50 or 75 amperes in series. This necessitated a silica spacing insulator, usually sliding on a central support, but in C.A.T.5 hanging freely from the two stout 1·3-mm. filament loops. In these systems the resultant magnetic forces are radial, and so small that the weight of the filament and insulator and the viscosity of the tungsten suffice to preserve the shape.

For smaller currents in the limbs, e.g. C.A.M.2 with $12\frac{1}{2}$ amperes, C.A.M.3, C.A.M.4, and C.A.T.6 with 35 amperes, and for higher wattage C.A.T.9 with 50 amperes, the series connection would give voltages about twice the preferred value of 20 volts, so the two loops had to be connected in parallel. In C.A.M.2 the currents were so small and the limbs so short that the magnetic forces were still negligible, but in the others special steps proved to be necessary.

In such systems the resultant force is larger, and is more effective since the loops are twice as long. It acts slightly outwards of the circumferential direction, and any distortion tends to increase the force, not decrease it as in the series case. To counteract it, each limb is given an appreciable preliminary distortion in two ways. The ends of each loop are set 6 mm. apart, which is closer than the 10 mm. separation of the central parts, and again both loops are bent in their own planes so that the ends are 14 mm. apart. The resulting shape of each loop is that of the gunwale of a boat, with a rise to bow and stern. The tension required to keep the loops so shaped in equilibrium is applied partly by the weight of the sliding central support, and partly by a spring acting on its outer end and pushing it downwards. The resulting system is stable throughout life, though, if the spring is defective, distortion becomes apparent after a few hundred hours.

It will be noted that in the parallel connection the tips of the loops are at the same potential and require no spacing insulator. Now the advantages of the series connection can be recovered if good electrical connection is made between the tips of the loops, and the supply leads are forked and crossed so that similar polarities appear at opposite ends of a diameter. The currents then run opposite ways in alternate limbs, as in the series case, and also—which is a great advantage—points at the same level on alternate limbs are at the same potential, and can be connected by finer wires, the tensions developed in which can counteract the resultant magnetic forces.

This principle of construction can be extended to include any even number of limbs, and it is adopted in all the larger types of valve. Thus C.A.T.10 has 6 limbs with triangular bracing wires, C.A.T.12 the same number on a wider base, C.A.M.6 8 limbs with square bracers, C.A.M.5 12 with interlaced triangular bracers, C.A.T.14 16, and C.A.T.19 24, the two last-mentioned with interlaced square bracers. The thick molybdenum leads are blackened to assist dissipation of heat by radiation, and are sawn into the required number of segments, and these are then bent to a jig so that they interlace accurately when assembled. The filament ends are arc-welded directly into holes or slots in the ends of the leads. This gives a slightly brittle joint, but, if required as in C.A.M.2, this brittleness can be dealt with by providing a clamp between the arcing point and the body of the filament. After arcing at the support end, the limbs of the multiple systems are adjusted to come together symmetrically at the far end without strain, and are then arced either all together in one operation, or in succession to a flexible ring of sheet molybdenum. The cross-bracing wires are then fitted in small V bends in the limbs placed to receive them. The spacing of the bracers is determined by the weight of the filament system below each bracing level.

The resulting system should be free from strain, but any residual strains are removed by raising to incandescence in a neutral atmosphere.

Appreciable distortion in after life is very rare. The stability of the system against electrostatic forces was established by means of a model in which weighted chains were substituted for the filaments.*

The presence of the cross-bracers also prevents an effect which had been troublesome in the smaller systems. This is the curious fact that the natural frequency of transverse elastic vibration of a tungsten filament, whatever its diameter, having the length required for a 19-volt working potential-drop between rigidly fixed points, is always very close indeed to the 100-cycle frequency of the magnetic forces due to a 50-cycle a.c. heating current. This natural frequency varies over a range of 20 % between cold and working temperatures, and therefore a resonance can easily occur during heating up, and, if the voltage applied results in currents in excess of the normal passing through the cold and brittle filament, the consequent vibrations in the plane of the loop can be notably destructive, breaking the loop at the tip. In the design of C.A.T.9, the natural frequency has had to be lowered to a safe value by making the ends of the supports themselves flexible in the plane of the vibration.

* Le Rossignol and Hall, see Reference (2).

As in the case of the cathode seals there is no obvious difficulty in constructing still larger cathode systems on the free-hanging principle. Indeed, the mechanical stability is unaffected as the diameter increases, so that once the narrowest practical system, seen in C.A.T.10, was found satisfactory, the way was seen to be clear for larger systems.

Cathodes are still generally heated by direct current, but if more than two seals are provided, which on the present systems can readily be done, polyphase alternating current can be used, and in particular with four seals the hum-reducing connection using two phases in quadrature or otherwise.

(k) Cooling of anode

The rate of transfer of heat from the anode surface to the cooling fluid is so high, of the order of 1 kW per sq. in., that the actual mechanism of the process may be peculiar to valves. This has been investigated.* Space does not permit description of the work, but the results may be briefly summarized. The surface temperature of the anode is found by an embedded thermocouple to reach the boiling point of the liquid at comparatively low power dissipations. Various oils were studied, as well as water. Thereafter it can rise very considerably, as much as 40 degrees C. in some cases, even at our usual somewhat conservative rated dissipations. Heat transfer at these high rates is evidently facilitated through the formation of small bubbles of vapour, or of dissolved air if present, which break up the stagnant film of liquid in contact with the anode. Further, there must be some transfer in the form of latent heat of condensation of the vapour.

These processes evidently provide a very effective convection of heat, quite apart from the general motion of the liquid over the surface. It is thus doubtful if spontaneous turbulent motion is really necessary, and it may be remarked that, according to Osborne Reynolds's laws, mere constriction of the space between anode and jacket does not increase the probability of turbulence for a given volume of fluid passing. It should reduce the thickness of the effectively stagnant film, and seems to do so at the lower dissipations, but at the higher it also definitely retards the break-up of the film by small bubbles. At the higher dissipations certainly the results show that constriction can be a disadvantage. This is further illustrated in the case of low μ modulator valves, in which the bombardment is focused on the anode in streaks, and, in consequence, the cooling conditions become more complicated. Here constriction of the jacket lowers the temperature only a little, and is accompanied by irregular flow, setting up severe vibration. Probably the flow is intermittently diverted from the hot streaks by formation of large bubbles trapped by the constriction. The focusing effect has other curious results, which show that it is the overriding factor in such valves. Thus, if the anode voltage be fixed and the kilowatts dissipated be reduced by increasing the grid bias, the streak temperature is practically unaffected over a range of some 6 : 1 in dissipation, sharper focusing compensating for reduction in dissipation. Again, increase in anode diameter can increase the streak temperature owing to sharper focusing; it does so in C.A.M.4 as compared with C.A.M.3. Between the streaks the temperature does not rise above the boiling point. These valves are very sensitive to the cleanliness of the anode surface. If hard water is used a temperature of 250° C. can be attained.

More recent work appears to show that a forced air blast can be substituted for liquid cooling in any type of valve operating, as is usually the case, somewhat below the rated dissipation for water-cooling. For this, the surface for heat transfer is very greatly increased by soldering to the anode either blocks of copper perforated by a great number of holes, or a very closely spaced set of radial fins. By this means the anode temperature can be kept down to 140° C., which, as we have seen, is a quite usual value for water-cooling.

* Le Rossignol and Hall, see Reference (2), p. 9, Fig. 12.

EVACUATION—THE EQUILIBRIUM STATE

(a) General

The general principle followed in all exhaust schedules is to subject each part of the valve for a sufficient time while it is on the pump to conditions more severe than it will meet with in operation. Thus the filament is overburnt, at the cost it may be of a few hundred hours of life, the grid is heated by bombardment to just short of the point where appreciable evaporation from the hotter parts would occur, and the anode is overheated with or without water-cooling—and we have already seen that even with water-cooling there can be considerable overheating given sufficient overload. The anode is not necessarily bombarded at all.

In the types which have bright emitting filaments no getter is used; as we shall shortly show, it is not needed. Independent evidence that this procedure has a sound basis is provided by the observed fact that gas evolution from heated metals and also from glasses is enormously reduced by a relatively small lowering of the temperature.

In addition to higher dissipations, higher voltages are applied in order to accelerate the fatigue of any tendency to flash-arc breakdown in the insulating properties of the vacuum, there being, as we have seen, no other insulation which is under any serious stress.

The schedules are judged by their results, and, where numbers permit, statistically, and in the light of reports of performance in operation.

This kind of procedure is necessary if the reliability of the product is not to be jeopardized by changing the schedules in ways which may prove to be ill-advised. Clearly, however, the further it is removed from the plane of trial and error by increasing insight into what is actually happening in the valve in manufacture and in operation, the more quickly will improvements be made and faults eliminated.

The true nature of the accepted gas test and the general behaviour of residual gas in valves with substantially cold anodes thus came in for investigation, and in both cases the results were somewhat surprising. Naturally, what was happening to the gas was much better understood when the test had been studied, so we shall take the work on the test first.

(b) The gas test and its meaning

The discriminating test is the now well-known backlash or gas test, in which the reverse grid current or "backlash" is measured under standard conditions of anode voltage and dissipation, the grid being necessarily negative. The backlash ratio is defined as the ratio of reverse grid current to anode current, and is usually expressed as microamperes per ampere. At a relatively late stage in the development of standard methods of exhaust it became clear that for hard valves the interpretation of the backlash test was more complex than was at first supposed. The simple ionization gauge law does not apply, i.e. the backlash ratio is not directly proportional to the equilibrium pressure. The factors which led to this conclusion are stated and discussed later, but to simplify the discussion a brief summary of the explanation is given at this stage.

In order to account for the observed behaviour of the backlash ratio r, it is necessary to assume that the reverse grid current contains two components: (1) the positive ion component r_p obeying the ionization gauge law which is of major importance for soft valves, and (2) a component r_0 of unknown origin which is of major importance for hard valves, where $r = r_p + r_0$. The experimental investigation was concerned, therefore, with the nature of r_0. Analysis of various test results had shown that r_0 continues to exist at substantially zero pressure; the residual grid current cannot, therefore, be a positive ion current, and must be an emission of electrons from the grid.

Consideration of the mechanism of this emission proved it to be photo-electric in origin, and caused by exposure of the grid to soft X-rays produced at the anode surface.

The principal features of the test results which the investigation had to explain, were as follows:—

First statistically, i.e. from large numbers of valves:—

(1) In a series of valves of identical construction the backlash ratio is never observed to fall below a certain limiting value. This needs little explanation on the photo-electric theory, because if gas were entirely absent, the backlash ratio would reach the limiting value r_0.

(2) Of freshly pumped valves, the majority show backlash ratios near to the limit, and few stray upwards to as much as 50 % more. This spread is unlikely to be due entirely to variations in gas pressure, owing to the enormous clean-up capability of water-cooled valves (described later). It is due only partly to slight changes in gas pressure, but partly to variations in the photo-electric component caused by adsorbed gas or traces of other impurities on the electrode surfaces.

(3) For valves differing in little besides the material of the grid, the limit is distinctly lower for molybdenum grids than for tungsten grids. For any type of valve r_0 for molybdenum is about 70 % of r_0 for tungsten. No satisfactory explanation could be found for this observation before the photo-electric theory was advanced, unless it was assumed that the residual gas pressure was actually lower in molybdenum grid valves, owing to gettering by the more volatile molybdenum. Although the residual pressure in a well-pumped valve is close to the limit of measurement, such a difference, if it exists, should have been detected by ionization gauge measurements. However, the photo-electric theory provided the explanation, as it was found that under the action of soft X-rays from copper the photo-electric emission from molybdenum is about 70 % of that from tungsten.

(4) For valves differing only in the diameter of the anode, the limit is lower the greater the anode diameter.

It was this last observation, more than any other, which led to a detailed investigation of the real meaning of the backlash test. For, if the reverse current is due entirely to gas, one would expect the backlash ratio to be greater in large anode valves because the electron paths are longer, and therefore more positive ions are produced. It was thought at first that for some reason the equilibrium pressure might be lower in large anode valves; and to decide the point a double valve having identical, but separate, grid-filament systems, and anodes of different diameter, was assembled inside a common envelope. This valve was known as the "Siamese Twin," and took the form of two valves with their anodes joined end to end, so that the communicating hole had the diameter of the smaller anode. There could thus be no question of a difference in pressure. Now when this double valve was hard, it was found that the large anode valve showed the lower backlash ratio. If the gas pressure was increased, however, the behaviour was as expected, and the backlash ratio increased more rapidly in the large anode valve, which eventually gave the higher backlash ratio. The pressure at which the backlash ratios were equal was about 2×10^{-5} mm. of mercury for anode diameters of $1\frac{3}{4}$ in. and 3 in. This result demonstrates clearly that for well-pumped valves gas ionization contributes little towards the reverse grid current.

Now, on the photo-electric theory the explanation is quite simple. As the anode is moved further away from the grid, the X-ray intensity at the grid surface and, consequently, the photo-electric emission fall off—inversely as the anode diameter for a circular cylindrical system. This is in good agreement with observations on different types of valve where anode diameter is the major variable.

Secondly, in addition to the above information from finished valves, we have, as a result of experiment:—

(*a*) For valves near the limit, the reverse grid current is proportional to the anode current at constant anode voltage, i.e. the backlash ratio shows little or no variation with the anode dissipation. This, of course, is true whether the grid current consists entirely of positive ions or of photo-electrons. It is only in very soft valves that the backlash ratio is appreciably affected by anode dissipation.

(*b*) For valves which are not fully bombarded, the backlash ratio is higher than for fully-pumped valves, although the residual gas pressure may be the same for both. A separate X-ray photo-electric experiment showed that for constant conditions of X-ray generation the number of photo-electrons liberated depended on the state of the molybdenum and tungsten surfaces. For surfaces which are treated in the same manner as grids for cooled-anode valves, adsorbed gas produces an increase in the photo-electric emission.

(*c*) For valves near the limit, the backlash ratio varies in a characteristic manner with the anode voltage

(see Fig. 2).* This observation was at first as mysterious as the variation of backlash ratio with anode diameter. According to all experiments on ionization by collision, an increase of anode voltage in the range of voltages used should have resulted in the production of rather fewer positive ions, and, consequently, in a lower backlash ratio. However, the photo-electric theory disposed of the mystery, for reference to Fig. 4 will show that the curve relating photo-electric emission from molybdenum with X-ray exciting voltage is very similar to the backlash ratio-anode voltage curve for a molybdenum grid valve. There can be little doubt, therefore, that the increase of backlash ratio as the anode voltage is raised is caused by an increase in the photo-electric component of reverse grid current due to the increased intensity of the X-radiation.

It will be seen that the photo-electric explanation adequately fits all the previously anomalous observations. There has, of course, been no direct confirmation in an actual valve; such a test would necessitate screening the grid from X-rays, which is quite impracticable. However, the evidence in favour of this explanation is so complete that no doubt exists of its accuracy.

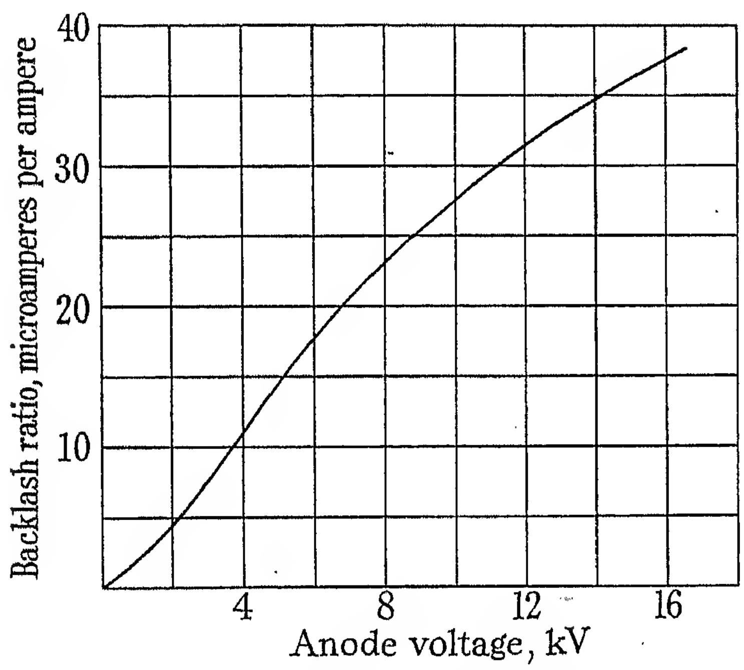


Fig. 2.—Variation of backlash ratio with anode voltage for a hard valve, type C.A.M.2 (molybdenum grid).

Other possible explanations were considered before the photo-electric theory was finally accepted. Various possible causes of grid current exist, including such factors as leakage across insulators, positive ion emission from the filament, and primary electron emission from the grid, but in water-cooled valves these factors, if present at all, are of negligible magnitude. Besides, the observed dependence of the residual reverse grid current on anode diameter and anode voltage narrowed the field of the investigation, and reduced the possible explanations to two:—

(1) The photo-electric explanation already discussed, and (2) an emission of electrons from the grid due to bombardment by high-velocity positive ions produced on the anode surface. This second hypothesis was also investigated experimentally in a valve having an extra grid placed close to the anode, by means of which the field at the anode surface could be reversed, thus preventing the escape of any positive ions formed there. The result of this experiment was entirely negative.

Photo-electric emission of electrons from tungsten and molybdenum under the action of X-rays from copper. It is impossible, in an actual valve, to separate the photo-electric component of grid current from the gas component. The apparatus shown pictorially in Fig. 3 (see Plate 2) was therefore built to study the emission of electrons from grid materials, i.e. tungsten and molybdenum, under the action of soft X-rays from copper.*

The radiograph is self-explanatory, and it will be sufficient to mention that the X-ray tube filament corresponds to the valve filament, the copper anti-cathode to the valve anode, and the photo-electric plates to the grid, either tungsten or molybdenum. Hence the X-ray tube voltage is analogous to anode voltage, the X-ray tube current to anode current, and the photo-electric emission to grid current. The ratio of photo-electric emission to X-ray tube current is therefore analogous to the residual backlash ratio.

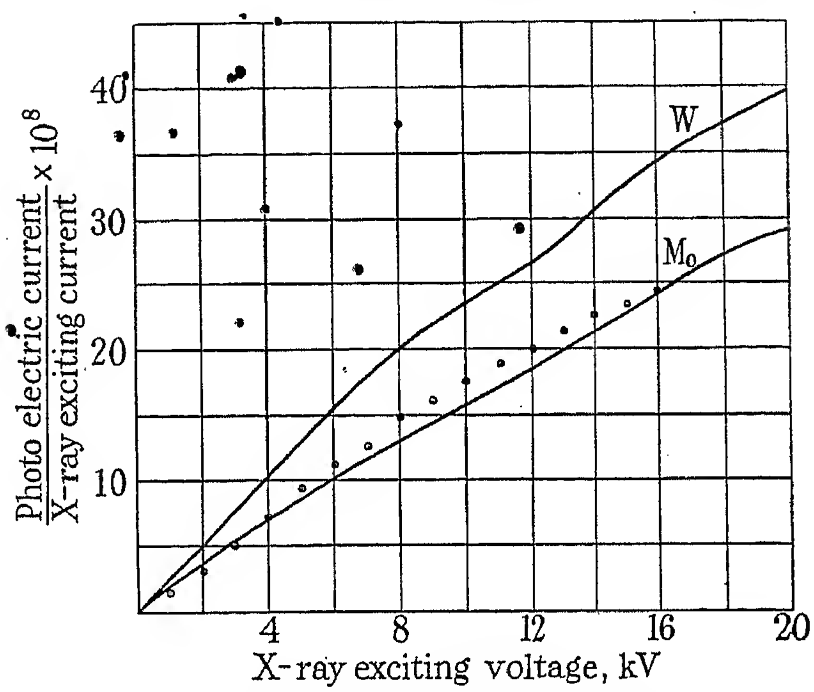


Fig. 4.—Photo-electric emission from clean tungsten and molybdenum under the action of soft X-rays from copper.

The points ⊙ are backlash ratio points, taken from Fig. 2 for a hard molybdenum grid valve (ordinates adjusted to fit at 16 kV).

Fig. 4 shows the result obtained after thorough degassing of the photo-electric plates. The increase of photo-electric emission as the X-ray exciting voltage is increased is due to the increased intensity of the soft radiation, and not to the appearance of progressively harder rays. This was proved by tests with an aluminium absorption screen. Tungsten shows a greater photo-electric emission than molybdenum, the ratio being approximately that previously observed in valves.

It will be seen from Fig. 4 that the qualitative agreement between the experimental results for molybdenum and a molybdenum grid valve is good, and the agreement

* The pursuit of this investigation was encouraged by information from Mr. C. R. Burch, that curves similar to that of Fig. 2 were normally obtained from continuously-pumped valves of the Metropolitan-Vickers demountable type.

* See Reference (4).

for tungsten is equally close. Quantitatively, the results obtained from the experiment just described may be used to calculate, by considering the relevant solid angles, the value of r_0 for a valve of any given geometry. Firstly, for a modulator valve having a parallel wire or "squirrel cage" molybdenum grid the experimental results predict a value of r_0 of 14×10^{-6} at 13 kV, whereas the observed value is 29×10^{-6}. Secondly, for a high μ tungsten-grid valve, the predicted value of r_0 is 28×10^{-6}, and the observed value is 45×10^{-6}. In both cases the calculated value is low, which may be due to an enhanced photo-electric emission in the valve caused by secondary X-rays.

The effect of adsorbed gas or other contamination on the molybdenum and tungsten plates was examined in terms of the volume of gas cleaned up before the equilibrium pressure starts to rise.

The volume of gas required to exhaust the clean-up capability completely has not been determined, but for a valve having a volume of about 1 litre several cubic centimetres of air at normal temperature and pressure have been cleaned up under experimental conditions without by any means exhausting the clean-up capability. This corresponds to a reduction in pressure from 1 mm. of mercury to less than 10^{-6} mm. of mercury. Of course this degree of clean-up was not carried out in one stage. The experimental procedure, having first of all exhausted the valve in the normal manner, was to admit the gas in small doses, each dose being cleaned up before the next was admitted. Clean-up was produced by operating the

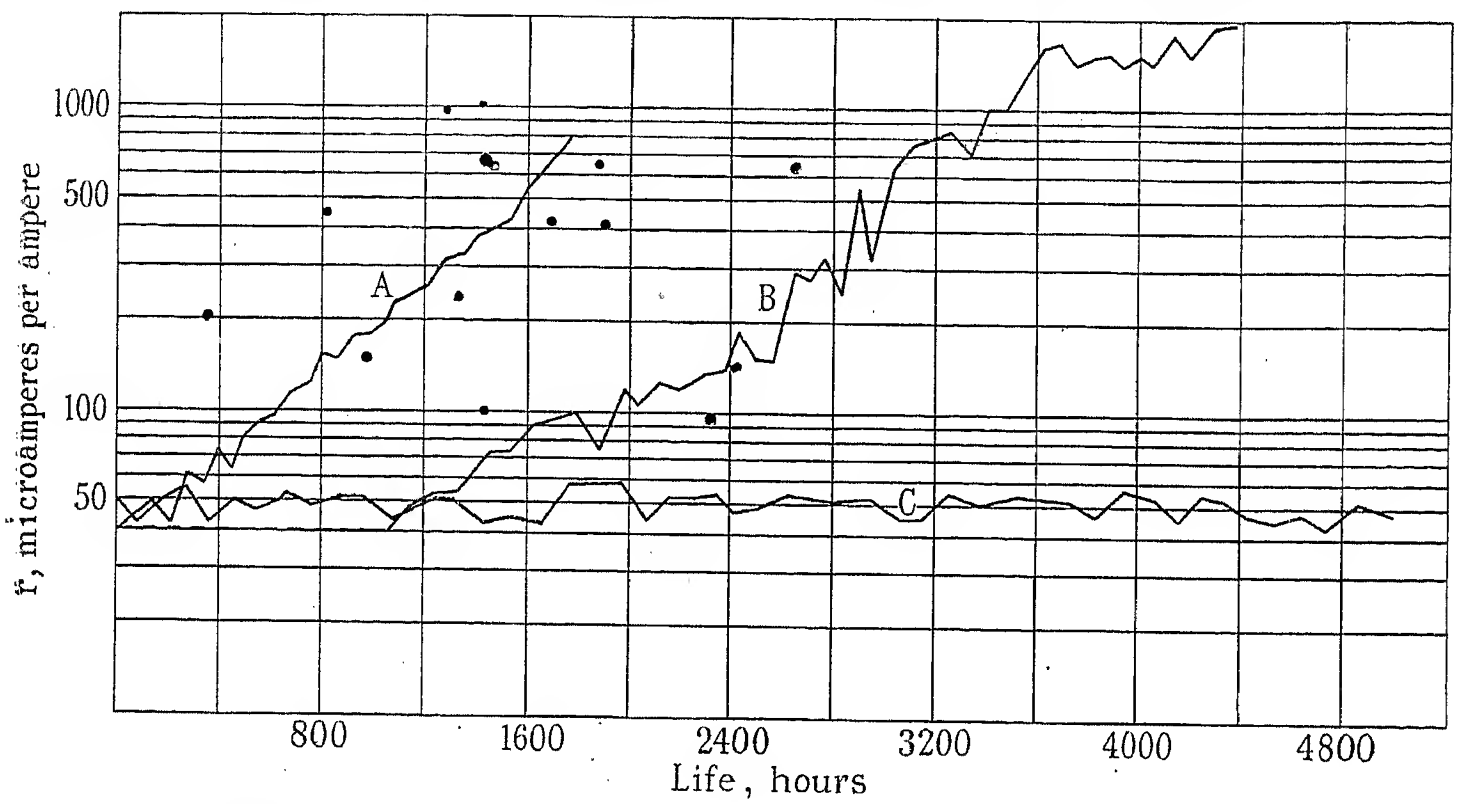


Fig. 5.—Variation of backlash ratio "r" for valves which soften during life.

Curve A. Valve with continuous source of gas and poor clean-up capability.
Curve B. Valve with continuous source of gas and greater clean-up capability.
Curve C. Valve with no serious source of gas and large clean-up capability.
Valve Type C.A.T.6.

the experimental apparatus. It was found that, after heat treatment corresponding to normal pumping of a valve, gas contamination increased the photo-electric emission, although other forms of contamination could reduce it. Hence, small changes of backlash ratio are not necessarily due to changes of equilibrium pressure, but may be due to traces of adsorbed gas or other contaminant on the electrode surfaces.

(c) Clean-up of free gas

A fully-exhausted water-cooled valve, with its large and very clean metal surfaces, forms a most effective pump and is capable of cleaning up surprisingly large quantities of free gas. Bearing in mind this large, but limited, clean-up capability, it becomes clear that one of the objects to be kept in view in developing exhaust schedules is the production of a valve capable of cleaning up, if required, the largest possible amount of gas liberated in operation. The clean-up capability may be measured valve under backlash test conditions which are known to be favourable.

This explains the recovery of valves accidently softened, for example through failure of the water supply. Cases have been recorded where such an accident caused the pressure to increase to the point where a glow discharge occurred, but operation of the valve under backlash test conditions with gradually increasing dissipation soon restored the vacuum to something approaching its original value.

Certain operating conditions are conducive to clean-up, notably those in which anode current flows when the grid is negative, at any rate for part of the operating cycle, e.g. normal "class B" or "class C" operation. Conversely, conditions in an absorber biased beyond cut-off when inactive, and passing anode current only when the anode potential is low and the grid is at a high positive potential, are not favourable to clean-up.

In practice this large clean-up capability renders the

se of getters unnecessary. This is illustrated in Fig. 5, where the variation of backlash ratio during life is shown for valves which are now known to have had a continuous source of gas, namely a small piece of very slightly overheated mica. Curve A is for a valve with a poor clean-up capability, i.e. it is saturated when only a little gas has been absorbed, and the backlash ratio starts to rise early in life. The valve, however, would have been satisfactory had there been no source of gas. Curve B represents a valve having a greater clean-up capability, and the same source of gas as A. Here the backlash ratio is unaffected for 1 000 hours, but once the clean-up capability has been exhausted the pressure rises. Curve C is typical of present-day performance, where the clean-up capability is large and there is no serious continuous source of gas.

The smooth curve of Fig. 6 shows curve B of Fig. 5

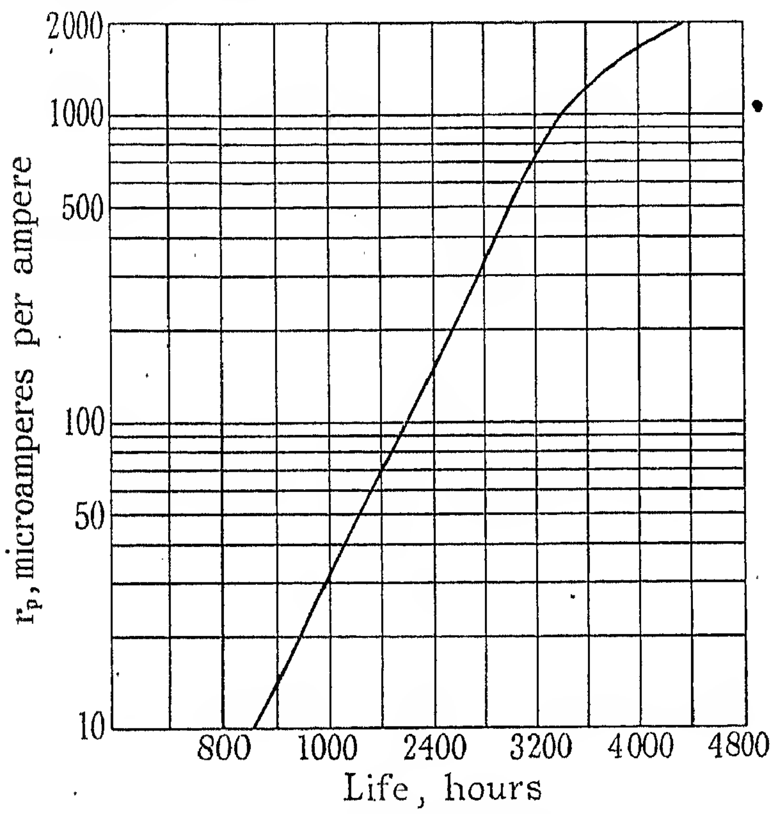


Fig. 6.—Variation of r_p, the gas component of backlash ratio, for a valve (type C.A.T.6) which softens during life. Curve B of Fig. 5 replotted after subtracting r_0, the photo-electric component.

replotted after subtracting the photoelectric component from the total backlash ratio, and it will be seen that the relation between time and the logarithm of pressure is linear over a considerable range. The straight portion is not always so long; but, nevertheless, it encouraged a search for a theoretical exponential relationship between pressure and time, but this could not be found on the assumption of a constant source of gas and clean-up by simple adsorption. However, this mechanism does account at least qualitatively for the general shape of the observed curve.

CONTROL OF SATURATED EMISSION

(a) General

Although it is possible to obtain uniformity of performance between valves of a given type without much attention to the design and performance of their cathodes by providing a great reserve of emission so that no valve approaches thermionic saturation, such a procedure is expensive in respect of valve life, and particularly so in the case of bright-emitting tungsten filaments in which evaporation at emitting temperatures is appreciable. Means are therefore necessary for ensuring that valves of a given filament design, selected by the methods described by le Rossignol and Hall,* are operated as nearly as possible at the same emission. The regularity of performance attainable by taking full advantage of these means is illustrated in a later Section (Fig. 19.)

When emission data for individual valves are available, the rated values of filament voltage and current become quantities of secondary importance, subject to minor adjustments which are made when each valve is installed. The range of adjustment needed in practice has become less and less as the possession of emission data has reacted on the technique of filament manufacture.

It is impracticable in a routine test to take the full emission from the cathode continuously because of damage to the valve through overloading, except in the case of some low-impedance rectifiers, and also because the test may be misleading through overheating of the filament ends by the superposed space current, and so forth.

Hence, either the electrode voltages must be applied intermittently, or a reduced emission must be measured. The intermittent-voltage method has long been used for glass valves, the peaks of space-current being read on a peak-voltmeter connected across a resistor.

(b) The reduced-emission test

For high-power valves in which the full emission may be some tens of amperes the reduced emission method is preferred. The principle of this is to record readings of filament voltage and saturated emission, the values of emission increasing in roughly constant proportion over a total range of about 20 : 1, and then extrapolate to obtain the filament voltage required for the full rated emission. Since a graphical method of extrapolation is the most convenient, some way of plotting in which the observed points lie on a straight line which can be produced upwards has to be established.

For taking the readings the filament is heated with alternating current, since with direct current local overheating of the negative end by the superposed space-current may not be negligible. It can readily be shown that with a heating current H leaving the positive end of the filament and space-current of wave-form such that it has a mean value S_{mean} and an r.m.s. value $S_{r.m.s.}$ the equivalent heating current for producing the same local temperature in a non-emitting filament is

$$\sqrt{(H^2 + S^2_{r.m.s.})}$$

for alternating current, and

$$\sqrt{(H^2 + 2S_{mean}H + S^2_{r.m.s.})}$$

for direct current. The effect on the local emission can be estimated from the local overheating so defined.

If a more general treatment of the distribution of overheating is required, the same formulae will be found to apply to each elementary length of filament, provided that only the space-current emitted from the part on the

* See Reference (2), p. 2, Fig. 2.

positive side of the element is used; its value has to be obtained by integration, starting from the positive end.

Since even bright-emitting tungsten is susceptible to emission-poisoning at reduced temperatures, the filament is flashed at the full voltage before taking readings, and then the lower emissions are taken first. Further, the positive voltage is applied to all the other electrodes together. This is again to reduce the chance of poisoning, since in a water-cooled triode, for instance, a combination of high anode voltage and low grid voltage can produce

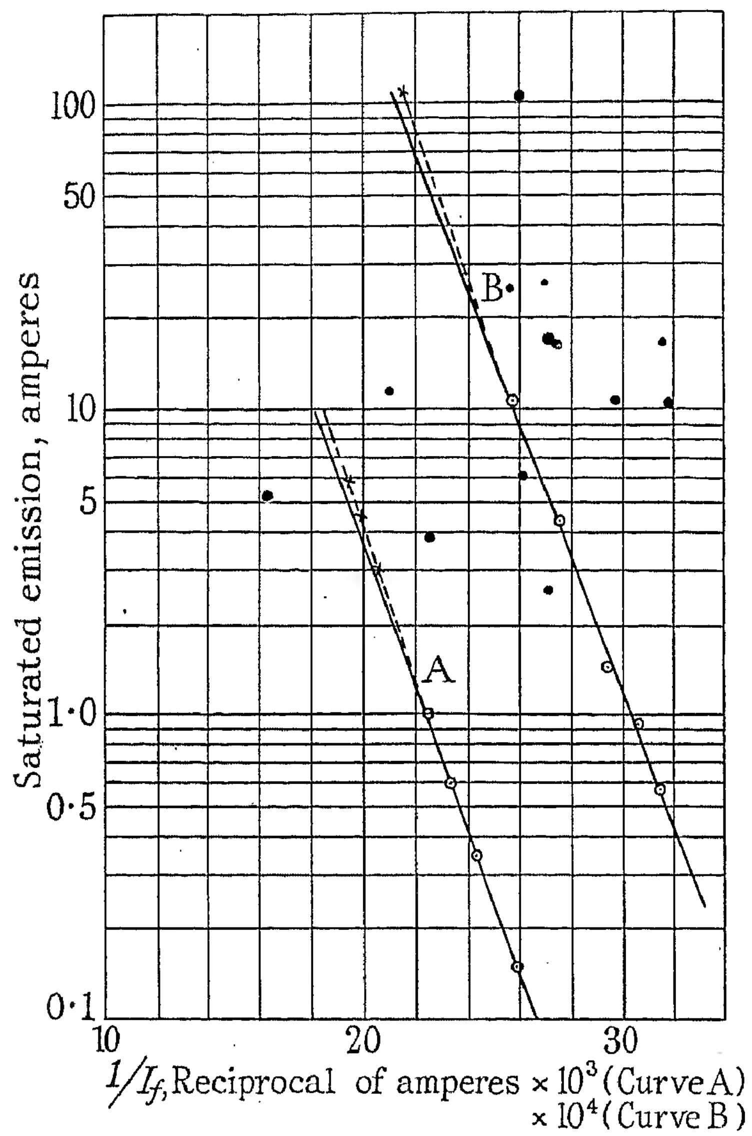


Fig. 7(a).—Extrapolation from reduced to full emission, simple method; log. of emission plotted against reciprocal of filament current.

Points ⊙. Normal test observations.
Points × (curve A). Additional observations for checking extrapolation.
Point × (curve B). Extrapolated point, using method of Fig. 7(*b*).
Curve A. Simple filament, valve type C.A.R.2.
Curve B. Multiple filament, valve type C.A.T.14.

poisoning, when a lower voltage applied to anode and grid does not. The control grid then takes up to about one-quarter of the total space-current, and if for the higher emissions the grid watts for full saturation are excessive, a lower positive voltage is used, and a small extrapolation to full saturation is made as described later in this Section.

(c) Extrapolation to full emission

Figs. 7(*a*) and 7(*b*) show two methods for the final extrapolation to full rated emission. Clearly the simple plot of log I_e against $1/I_f$ will only do for small extrapolations, although it is by far the best of such simple methods; whereas the method illustrated in Fig. 7(*b*) is much better, and this is, in fact, used for extrapolations up to as much as about 10 times the highest observed value.

The result of the extrapolation is to provide for each valve filament a "marked voltage" at which it gives a stated emission current which is 90 % of the value obtained from the plot, and is described as "90 % saturated." This 90 % figure is adopted as being more useful to users, since the slow final approach to full saturation makes it unlikely that the 100 % value will ever be used in practice.

The plot is not necessarily made for every individual valve. In many types it is found sufficient to determine from a number of plots a standard extrapolation factor. For example in one well-known type, C.A.T.14, the "marked voltage" for 100 amperes 90 % saturated (111 amperes full saturation) is found to be 1·31 times the voltage observed for 10 amperes fully saturated, and the factor for that type is 1·31, which can be applied to a single test reading at 10 amperes emission. The variation of the factor for individual valves seldom exceeds ± 0·7 %.

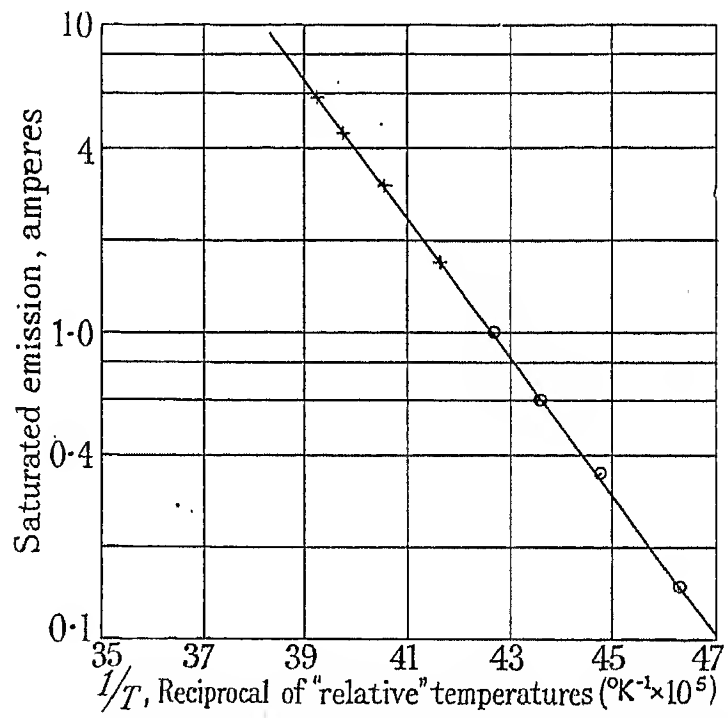


Fig. 7(b).—Extrapolation from reduced to full emission, standard method; log. of emission plotted against reciprocal of "relative" temperatures.

Points ⊙. Normal test observations.
Points ×. Additional observations for checking extrapolation.
Valve type C.A.R.2.

The method of plotting in Fig. 7(*b*) is based on the Richardson equation $I_e \propto T^2 e^{-b/T}$, but the T^2 term is negligible, and the T of the plot need not be a true temperature but can be anything whose reciprocal is a linear function of the true reciprocal temperature. The "relative" temperatures used for the plot are obtained by the following rapid approximation. The reading of filament current A is used and the corresponding relative temperature T_1 for a filament of length l_f and diameter d_f is found from Langmuir and Jones's* tables using the relation:

$$A = A' d_f^{\frac{3}{2}}; \; A' = \sqrt{(W'/R')}$$

* See Reference (5).

where A', W', and R', are the heating current, power dissipation, and resistance of 1 cm. length in a filament of 1 cm. diameter at temperature T_1.

This relative temperature T_1 then corresponds to current A, voltage V_1, and emission I_{e1}. Using Langmuir's second relation:

$$V = V'\frac{l_f}{d_f^{\frac{1}{2}}}, \quad \text{where} \quad V' = \sqrt{(W'R')}$$

the other temperatures T_2, T_3, etc., corresponding to the other voltages V_2, V_3, etc., are found, and the plot is made.

The series of voltmeter readings V_1, V_2, etc., is preferred to a series of ammeter readings A_1, A_2, etc., because the combination of voltmeter and resistor is considered to be more permanently reliable than that of ammeter and current transformer, and because even proportion over the range of temperature. There are two checks on the process available, one is to verify it directly with a plot of readings taken all the way to full emission without extrapolation, using a low impedance diode such as a standard water-cooled rectifier. This has given a very satisfactory confirmation, as illustrated by the points X in Fig. 7(b).

The other check is to calculate from the slope of the plot the value of the coefficient corresponding to the b of Richardson's equation, and it is found that when this is done the values of b obtained agree closely with the accepted value of b for pure tungsten.

(d) Emission statistics

The results of the reduced emission test for the first 61 valves to which it was applied are shown in Fig. 8, the

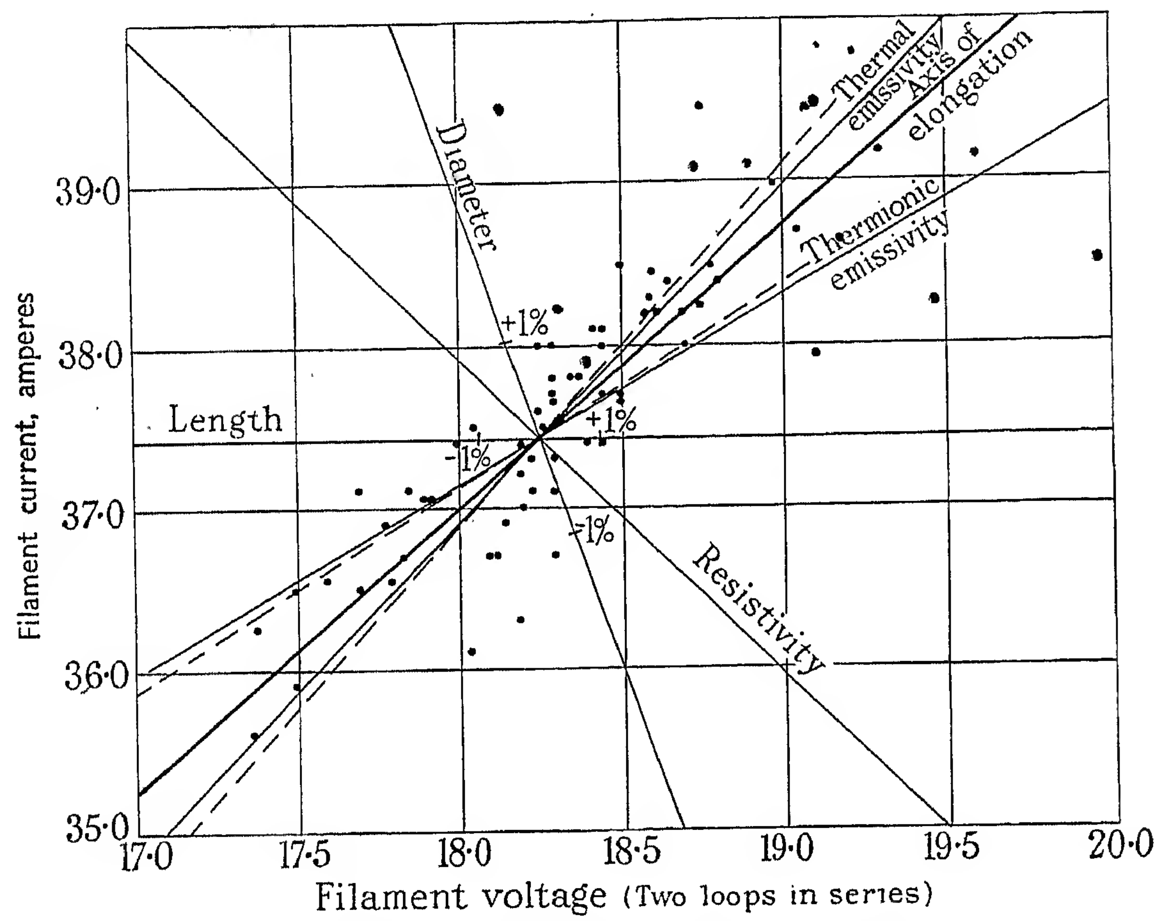


Fig. 8.—Reduced emission test, target diagram, showing axes of elongation expected from variation of each quantity (as marked) alone. Early valves (type V.T.26).

a slight error in converting from amperes to volts after extrapolation might be serious.

Other similar methods have been examined, but the one here followed is found to be the most accurate. Since the voltage readings are actual terminal voltages, this process ignores corrections for graded cooling at the ends and supports of the filament, but these corrections are known to vary little over the range of temperature in question. This is one reason why the temperatures plotted are only "relative." Another and more fundamental reason is that the resistance property R' of the actual filament may not be the same as Langmuir's, nor the radiation property W' of the actual filament in its actual surroundings, which may vary in temperature and in reflecting power. Nevertheless, this will not matter so long as these properties preserve a due

position of each dot representing the amperes and volts required to produce the standard emission current, 1·0A 90 % saturated. The extreme range of variation is ± 5 % in volts and amperes, i.e. $\pm$ 10 % in watts.

The marked elongation of the pattern indicates either that the observed variations had only one physical cause, or that if there were more than one cause then the several causes must be such as to produce closely similar effects. The axis of the elongation has been determined by the method of least squares; if a larger number of observations had been available, the direction of the axis might have been a little different, but the chances are 20 to 1 against it ever, for any batch of similar size, lying outside the broken lines, on either side of the axis shown.* Each of the other "axis lines" indicated on

* See Reference (6).

the diagram shows to a close approximation the direction which the elongation would have taken if only one physical quantity, that marked on the axis, had been subject to variation. Thus, to take the simplest case, variation in length will affect the voltage, but not the current, required to bring the filament to a given temperature. To reproduce the standard emission there would have to be a readjustment of the temperature to compensate for the change of area. Since, however, the emission varies very rapidly, this readjustment would be very small, so that the "length axis" will be a substantially horizontal line, as shown.

The direction of the actual elongation lies very close to the axis of thermal emissivity, that is, of the variation in watts required for filaments of the same dimensions and resistivity owing to variations in their thermal radiation to their surroundings. Under these conditions the resistance is constant, and the current and voltage will increase or decrease together and to the same extent, as the direction of this axis shows.

It is interesting to note what would be the effect on the diagram of variations in length and diameter,

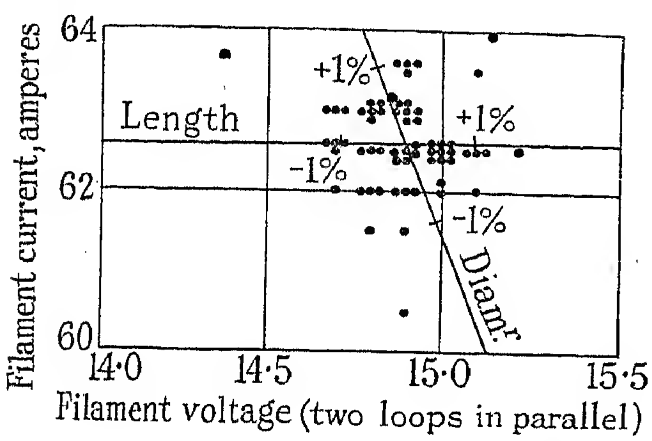


Fig. 9.—Reduced emission test, target diagram. Recent valves (type C.A.T.6).

separately or together. These filaments were actually some 230 mm. long, so that variation in length exceeding 1 % must be regarded as very unlikely. The drawing of the wire is not, however, so easy to control, and variations of this order in diameter are much more probable.

Variations in length alone would thus produce only a very small elongation on the scale of the diagram; but variations in diameter would have a perceptible effect. Variations of both together would produce a small elongation in the direction of the diameter axis, but with some lateral spread. The point of interest is that a marked elongation in the direction actually observed could not result from independent variations of length and diameter, though the lateral spread could very well do so.

For such an elongation to result from variations in dimensions there would have to be a definite connection between the two, in the sense that all thin filaments would have to be short and all thick filaments long, and to a most unlikely extent. Since the two dimensions are under completely separate control this must be considered impossible.

The axes of thermal and thermionic emissivity are too close together for any definite distinction between these two causes to be made on the evidence shown in the diagram. All that could be said is that thermal emissivity is the more likely cause.

However, thermionic emissivity should be sensitive to heat treatment of any filament between repeated tests. No marked effects of that sort were observed, so that variations in thermal emissivity remained as the most likely cause of the observed elongation.

This conclusion indicated that the technique of wire drawing as affecting the final state of the surface of the filament required attention, and steps taken to ensure that filaments had a smooth bright surface resulted in a distinct and maintained improvement,* as exemplified in Fig. 9, showing the results of reduced emission tests on representative later valves of similar filament construction. The larger valves with multiple-filament systems containing more filament limbs must be expected to give still more uniform results, since these give an average of the performance of the individual limbs.

The improvement between the valves of Fig. 9 over those of Fig. 8 illustrates the value of a suitably designed and easily performed test on an isolated property of the product, once the meaning of the test has been sufficiently analysed.

SPACE-CURRENT CHARACTERISTICS IN THE OPERATING REGION

(a) General

The published characteristic curves for each type of valve are used for the purpose of choosing which type is best suited for a particular use. They are not apparently often used for predetermining refined details of performance such, for instance, as the percentage of modulation harmonics. Such predeterminations would require extreme precision in all parts of the curves, exact knowledge of circuit constants, and a good deal of labour in computation; in consequence, experimental study of optimum operating conditions is generally preferred.

Since valves which are expected to give a good life are operated with the filament temperature as low as possible, it is to be expected that there will be an approach to saturation in the part of the operating cycle where the space-current is largest. Now it is just where the space-current is largest that the valve is doing most of its work. Hence, it is particularly necessary that what happens in the region of the onset of saturation should be known, and together with this the effects of changes in the level of saturated emission.

To get characteristics directly by static readings is frequently just possible without undue risk to the valve, but high-power plant is needed. Further, static characteristics are liable to be misleading whenever the space-current is a sufficiently large fraction of the filament heating-current to influence appreciably the emission level—through ohmic overheating of the ends of the filament and "emission cooling" there and elsewhere.

Dynamic methods using peak-recorders or cathode-ray oscillographs are safer for the valve, but are liable to require even more plant. So a good many years ago, before cathode-ray oscillographs such as we have now were available, a simple method was devised by which

* See Reference (7).

space-current characteristics could be extrapolated from low-power readings, and this still seems to be adequate.

Simple extrapolation by extending the observed lower parts of curves using the 3/2 power law is not of much use. The onset of saturation is too gradual, more so than may be generally appreciated.

The index of the power-law curve, as shown by the slope of a doubly logarithmic plot, Fig. 10, begins to decrease at not much more than one-half of the saturated current, and to reach anything like saturation the voltage has to be raised to nearly twice its value at this point of departure. This early departure is probably valuable in practice, for it about doubles the length of the straight characteristic, preclude explanation of this slow saturation to more than a very minor extent by most of the usual means, such as asymmetry of the collecting electrodes, screening of one part of the filament by another, and variation of potential, 20 volts (a.c.), along the filament itself. Some other reason or reasons have therefore to be found, and since the effect is but little greater in less-symmetrical valves as long as their filaments are straight, the reasons must be sought in the filament itself.

The most likely reason, physically, for the first departure is that there are local variations in the saturation value in different regions of the filament surface, and a

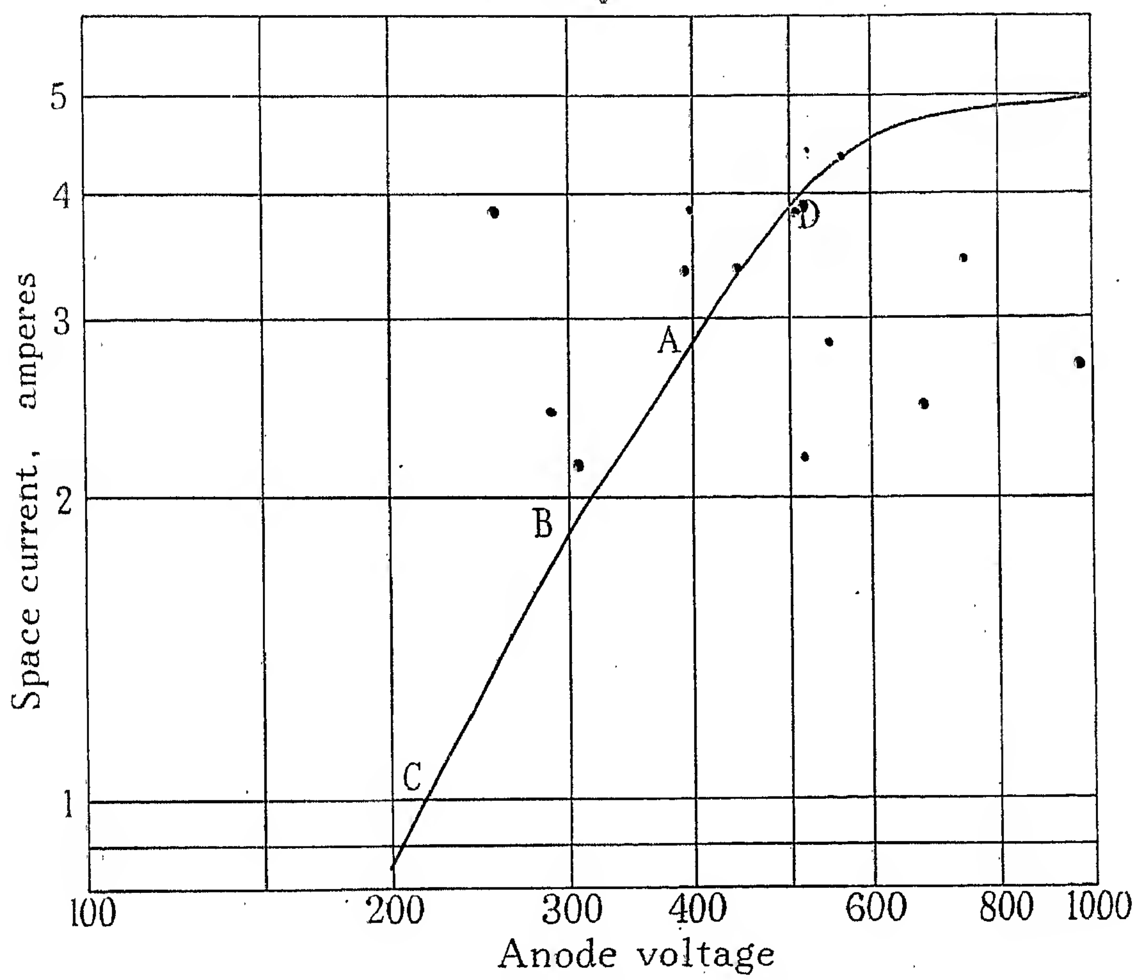


Fig. 10.—Characteristic (plotted to log. scales) of symmetrical diode (type C.A.R.2).

A. Departure from 3/2-power law.
BC. Incipient magnetron cut-off.
CD. Range of linear characteristic.

part of the characteristic; for present purposes, however, it is a complication. These effects are common to all types of valve, and seem largely independent of the geometry of their construction. The following analysis of the case of a geometrically simple valve can therefore be taken as being of general application.

This is the low-impedance rectifier type C.A.R.2, which has the " binocular " construction in which the filament consists of two straight limbs, each lying along the axis of a substantially complete cylindrical anode.* A doubly logarithmic plot of a characteristic of one of these valves is shown in Fig. 10.

Now in this kind of valve the symmetry of construction, the length (200 mm.) of the filament limbs, compared with their diameter (1 mm.), and the voltage-range of the calculation of the distribution of emission along the filament due to the end cooling, is found to account satisfactorily for the departure up to about 90 % of the saturation value, that is to say as far as anyone is likely to be practically interested in the characteristic. The calculation followed the methods of Forsythe and Worthing* and was verified qualitatively from the distribution of evaporation wastage in a long-life filament (see Fig. 17).

The method of extrapolation, to be described below, allows for any local variations in the saturated emission, whatever their cause.

It is, however, of interest to know the reason for the form of the uppermost part of the characteristic, since this might have some effect on the extrapolation. The

* See Reference (2), p. 13, Fig. 16; and also Reference (17).

* See Reference (8).

explanation, according to some work by G. W. Warren, shortly to be published, is that we have here a kind of "telescoping" of the Schottky effect,* that is, the increase of the emission above the normal saturation value owing to a finite and increasing field at the cathode surface. That so large an increase as 10 % in the emission can be produced by the observed increase of collector voltage, arises briefly from the facts that as long as there is a fully developed space-charge there is no field at the cathode surface, and that as soon as the space-charge is reduced by the increasing initial acceleration of the emitted electrons, the full field due to the potential of the anode, or the equivalent equipotential in triodes, etc., is quickly established there. The initial growth of the field, and therefore of the emission, is found to be rapid, hence the "telescoping" mentioned above, and the increase of voltage required to produce what we have been calling saturation, which is really the establishment of the true Schottky rate of increase, agrees very well with what is observed in the C.A.R.2 type of valve, i.e. some 300 volts in Fig. 10. The extent of the effect is really very largely

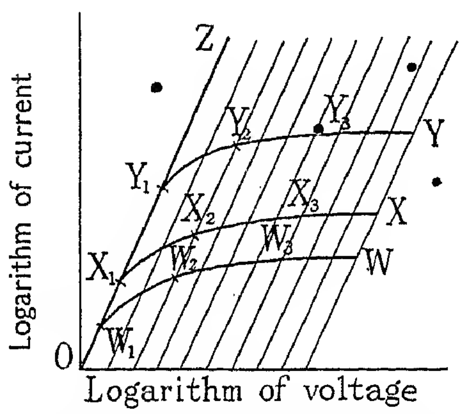


Fig. 11.—Diagram (plotted with logarithmic scales) illustrating extrapolation of space-current characteristic from lower to higher levels of emission.

a property of the filament itself, and its existence accounts for the outstanding discrepancy in an earlier analysis of a diode characteristic by one of the present authors,† and takes priority over alternative explanations, e.g. in terms of local variations of the field at the cathode surface.‡

After this analysis of the onset of saturation, we can now proceed to the method of extrapolation used. This employs a doubly logarithmic plot, logarithm of space-current against logarithm of electrode-voltage, and can be applied either to a diode, or to a triode with grid to cathode, or to a triode with grid bias, negative or positive, varied in constant proportion to the anode voltage, but with positive grid bias it is the space-current leaving the cathode that must be plotted.

If a number of curves for various levels of emission are plotted as in Fig. 11, the result at once suggests the method of extrapolation. We shall describe this in the first place as an empirical rule, and later discuss its probable theoretical basis.

The valve is usually connected as a diode, grid and anode together, so that only relatively low voltages and power are needed. One curve, OZ the "unsaturated" characteristic, is taken as high as grid dissipation permits, and at a filament voltage sufficient to ensure that there is no emission saturation, and another, OX, at the highest filament voltage consistent with reaching full saturation without exceeding the permissible grid dissipation. The other curve below OX is not essential, but is here included to illustrate the principle.

If lines parallel to OZ are drawn through points X_1, X_2, X_3, on OX cutting the lower curve OW in points W_1, W_2, W_3, the intercepts W_1X_1, W_2X_2, W_3X_3, are found to be very closely equal.

Hence to obtain a characteristic which saturates at a predetermined value Y, e.g. the saturation value at "marked volts," we simply extend the lines through X_1, X_2, X_3, parallel to OZ, and mark off Y_1, Y_2, Y_3, so that X_1Y_1, etc., are all equal to XY, i.e. to the difference in emission level. In practice OZ, except for very low currents, is usually very close to a straight line inclined at the 3/2-power angle.

If the valve had been connected as a triode, a curve would have been obtained which again is of the same form as OX, but displaced laterally to the right by a distance equal to $\log \dfrac{\mu + 1}{\mu[k + (1/\mu)]}$, where k is the factor of constant proportion between grid bias and anode voltage.

To calculate from OY the corresponding triode curves for various anode voltages, we have to replot OY, this time on ordinary paper, multiplying all voltage readings by $(\mu + 1)/\mu$, and then displace the curve so obtained by $- E_a/\mu$ successively in the ordinary way. The effects of changes of emission level, e.g. those due to changes of $\pm$ 1 volt on the filament, can be illustrated by a trifurcation of one of the curves.

The tail.

The lower parts of the curves towards cut-off are inserted from direct observation, since the dissipations are low. These lower parts do not follow the 3/2 power law, largely because of the superposed magnetron cut-off effect due to the field of the heating current, which may be between 30 and 75 ampères per limb. This effect is so strong that to get good readings near cut-off the filament current has to be held very constant. The displacement rule also may not hold here without modification, owing to progressive reduction of μ, as shown in Fig. 12, in which anode voltage is plotted against grid voltage for various anode currents. This form of diagram is convenient for extrapolating the straight lines of anode current to higher voltages than may be available. In types of valve which show a marked "tail" at the foot of a high-voltage characteristic, the lower lines on this diagram form a fan. However, in the C.A.M.3 type shown, and in other similar low-μ modulator valves, there is very little tail indeed. C.A.M.3 has four straight-filament limbs at the corners of a 10-mm. square within an octagon of grid wires 25 mm. in diagonal. The characteristics are the same whether the filaments lie behind four grid wires, or in the spaces between them. The absence of tail implies a high degree of uniformity of the field round the circumference of the filament in presence of the space charge, i.e. absence of *Inselbildung*.

* See References (9) and (10).
† See Reference (11).
‡ *Ibid.*, (12).

The addition of a fine spiral to the grid structure to increase the value of μ has little effect on the tail.

Division between anode and grid.

When the grid bias is positive, values of anode current have to be obtained by subtracting the corresponding grid currents from the total space-current. The grid currents are obtained by plotting the ratio of grid current to space-current against the ratio of grid voltage to anode voltage, as in Fig. **13**. On such a plot we find that outside the region of secondary emission all the plotted points corresponding to various permissible currents and voltages lie on a straight line, and it is assumed that values of grid current otherwise unattainable can be obtained from this straight line. Theoretically we should use $(E_g/E_a)^{\frac{1}{2}}$ for the plot instead of E_g/E_a, since that would be the rule for the simple repulsion of particles from a charged wire. This makes little difference, but E_g/E_a is better, perhaps because of the known development of space-charge round the grid wires. The secondary emission region will be considered later in this section.

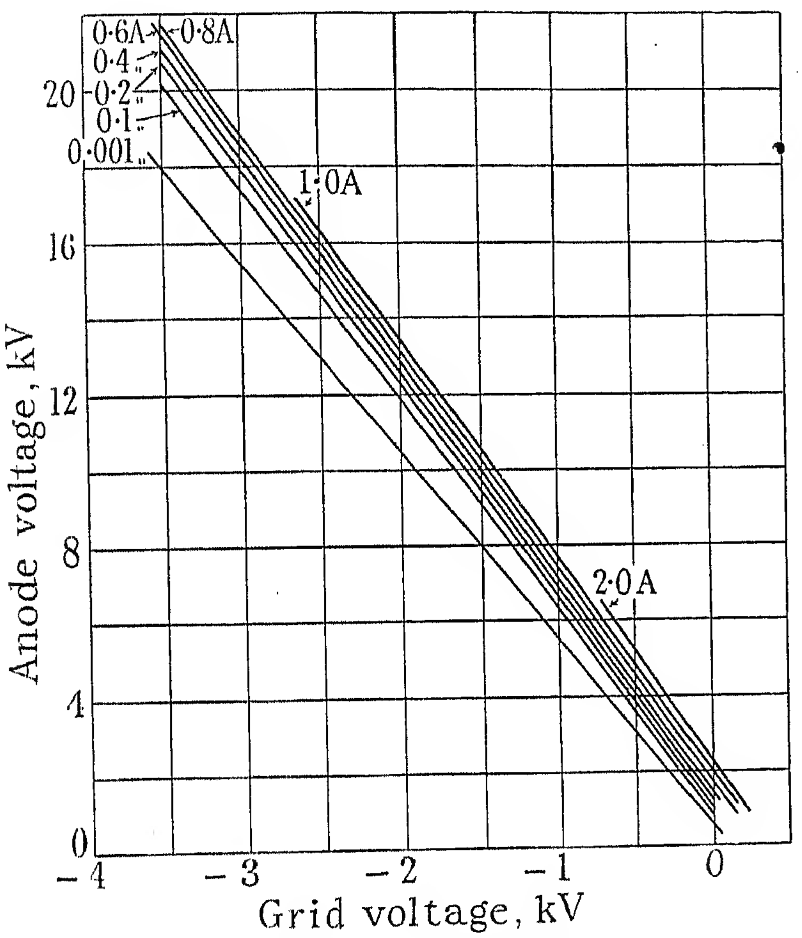


Fig. 12.—Current-contour characteristic of low-μ valve (type C.A.M.3), showing reduction of μ at minute currents only.

Theoretical.

Returning again to the main extrapolation on the doubly logarithmic plot, Fig. **11**, the theoretical justification of the procedure can be referred to the equations of motion of the electrons, but can be explained as follows:—

At any point of the curved portion of a plot, parts of the filament are emission- or temperature-controlled owing apparently to the end-cooling, and parts voltage, i.e. space-charge, controlled. Suppose now that we have a curve, e.g. OX, plotted up to the limit of dissipation of the valve, and we want to draw a curve, such as OY, up to a larger current, say up to n times the current. If we increase any voltage $n^{2/3}$ times, the currents from all the voltage-controlled areas will be increased n times, if the temperature is simultaneously raised by not too small an amount. Again, if we increase the temperature by means of the heating current so that the saturated emission of all parts is increased n times, the temperature-controlled parts will give n times the former current, provided the voltage is increased sufficiently to keep them saturated. If now we do both those things together, e.g. pass from X_2 to Y_2 on the plot, those parts which were temperature-controlled will remain so, and those which were voltage-controlled will also remain so. For, consider a boundary line dividing the two states of the emitting surface. On the one side the necessary excess of voltage, and on the other side the necessary excess of temperature, are still maintained, so that the boundary line does not move. The two areas on either side are thus the same as before, and as the two simultaneous adjustments ensure that the current from each is increased n times, the total current is increased n times.

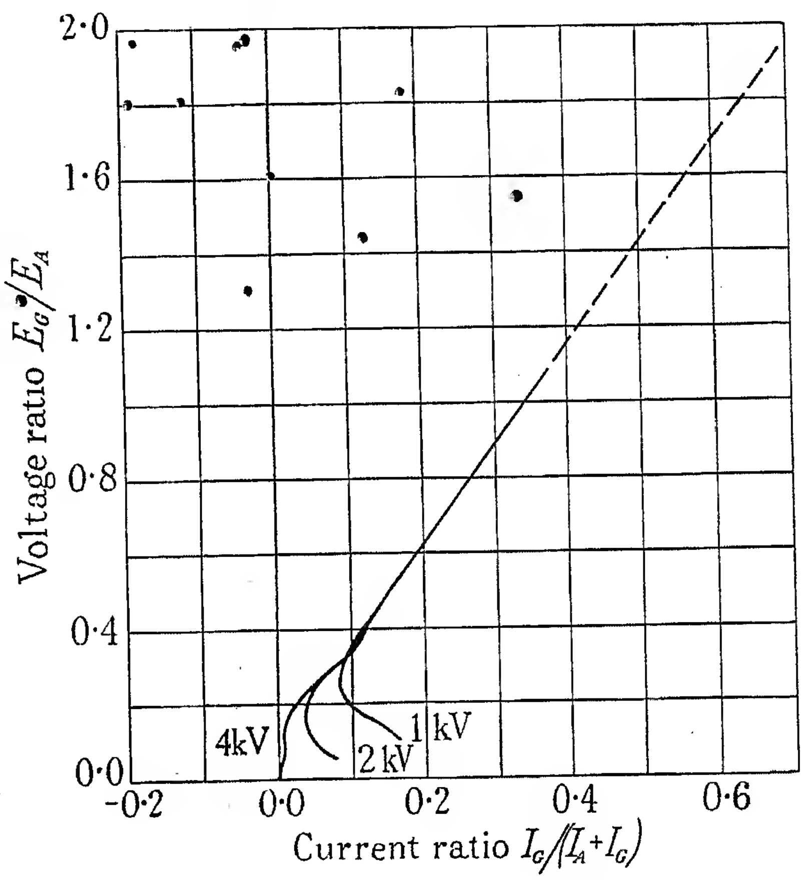


Fig. 13.—Division of space-current between anode and grid.

To sum up, we have arrived at the rule that from any observed characteristic any other can be obtained by increasing the temperature so as to produce an n times increase of saturated emission, and by increasing all controlling voltages $n^{2/3}$ times.

According to the argument, the rule can be applied without our having to know anything of the properties or circumstances of the various local areas of the filament,

provided only that we feel justified, e.g. by comparing two curves such as OW and OX, in supposing that they do not appreciably interfere with one another. It does not apply in the region of the telescoped Schottky effect.

(b) Grid-current characteristics

Secondary emission.

The general form of the lower part of the grid-current characteristics is decided to a large extent by the amount of secondary emission present. The secondary-emission coefficient (number of secondary electrons produced per primary bombarding electron) depends on the bombarding voltage and on the state of the bombarded surface. In general, an electropositive contaminant increases the secondary emission, and an electronegative one reduces it. There is comparatively little variation from valve to valve of any type, which indicates that the grid of a high-power valve represents a very clean metal surface, and the secondary emission coefficient is approximately that of the pure metal. In the absence of any

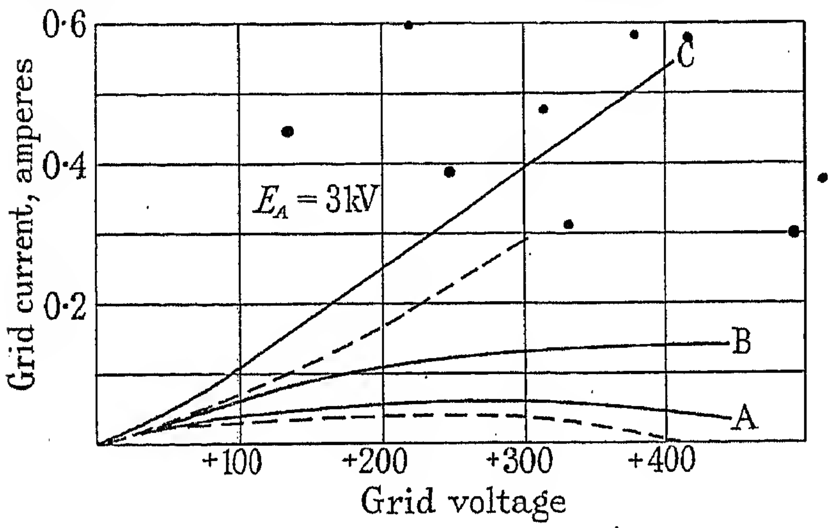


Fig. 14.—Control of the grid-current characteristic by movement of a grid band surrounding the cool ends of the filament.

The broken curves show the limits of valve-to-valve variation before control was applied.

Valve type C.A.T.6.

attempt to reduce the secondary emission, the type of grid-current characteristic often obtained is shown in Fig. 14 (lower broken curve). This can be dangerous for valves operated in circuits having high grid resistance, as the grid can reach and maintain a high positive potential, with consequent possibility of damage to valve and circuit components. Excessive secondary emission is therefore undesirable, and it became necessary to keep the magnitude of the effect under control. This can be accomplished in various ways. For example, the use of tantalum as a grid material results in low secondary emission, and the same result can be achieved by coating a tungsten or molybdenum grid with a substance, such as carbon, having a very low secondary emission coefficient. In fact it has been found that, if the internal surface of the anode is treated with carbon, sufficient finds its way on to the surface of the grid during pumping to produce a marked decrease in the secondary emission coefficient.

Apart, however, from the grid material, we have found that the secondary emission is not uniform along the length of the grid, but is much greater from the ends, which are opposite the cool ends of the filament, than from the central active region. Proof of this is obtained from the observation that dimming the filament results in enhanced secondary emission. This behaviour is fundamentally due to the temperature distribution along the length of the filament, and may be explained briefly as follows:—

Owing to the distribution of temperature along the filament, there is considerably more space charge around

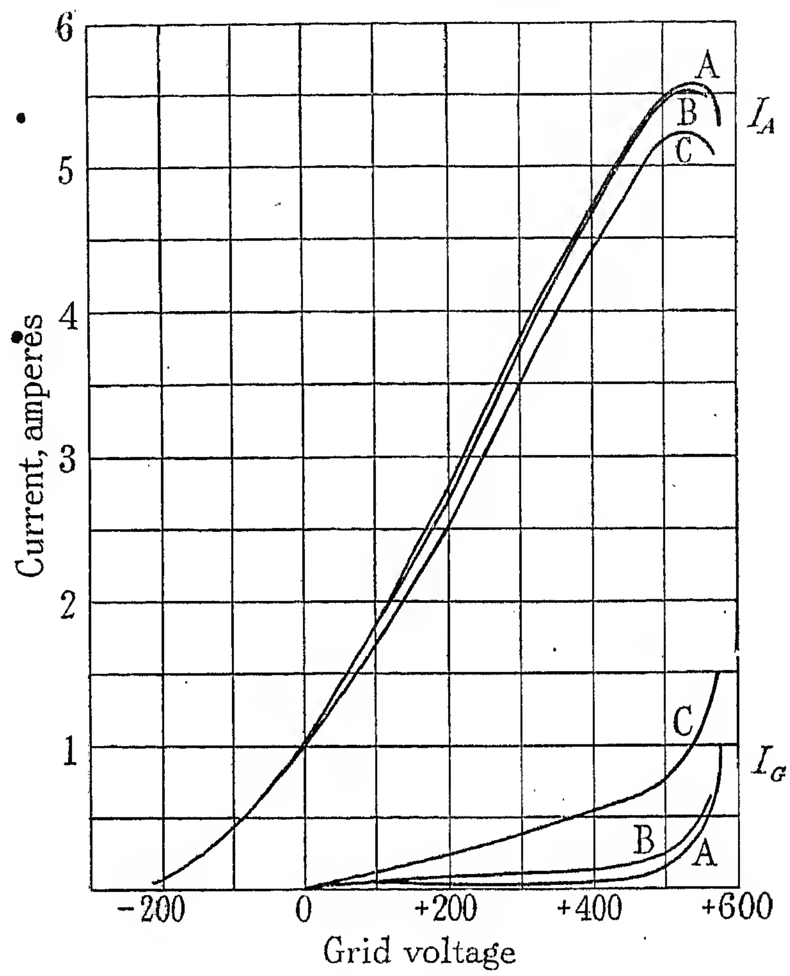


Fig. 15.—Effect on the "class B" operating characteristic of the distance by which the grid band overlaps the cool ends of the filament.

Curve A. Grid band overlap 2·5 mm.
Curve B. Grid band overlap 12 mm.
Curve C. Grid band overlap 20·5 mm.

Valve type C.A.T.6.

the grid wires in the central active region than at the ends. This causes the accelerating field tending to remove electrons from the grid to the anode to be stronger at the ends of the grid than in the active region. The ends of the grid therefore contribute a greater number of secondary electrons per unit length than does the active region. Now, if the ends of the grid instead of being an open structure are made in the form of a solid band surrounding the cool ends of the filament system, two things will happen. First, the ends of the grid collect more electrons, and, secondly, the secondary electrons, being produced on the inner surface of the band where the accelerating field of the anode is very weak, cannot escape, so that the effective secondary emission is reduced.

This effect was explored in a C.A.T.6 valve, having a movable grid band at one end of the grid, and the results will be seen in Fig. 14. Curve A shows the grid-current

characteristic when the band overlaps the filament system by only 2·5 mm., the length of the filament loop being 180 mm. Curve B shows that when the overlap is 12 mm., the effective secondary emission is reduced considerably, and with an overlap of 20·5 mm. (Curve C) the secondary emission is entirely swamped, but here the band covers parts of the filament at nearly full temperature, and steals anode current. The effect of these changes on the class-B operating characteristic is shown in Fig. 15. For type C.A.T.6 a grid-band position corresponding to curve B has been adopted, and other types are treated on their merits.

One of the results of secondary emission is that the number of watts dissipated in the grid cannot, under most operating conditions, be easily calculated. Even under static conditions the product of grid voltage and grid current only gives the true number of watts if there is no secondary emission. In order to measure the grid watts any instrument which gives a measure of grid temperature may be used, and perhaps the simplest method is the use of a surface thermopile as a radiation indicator. Although the amount of radiation from the grid is usually much smaller than that from the filament the sensitivity of the instrument is sufficient to give an accuracy of, at worst, 5 %, which is ample in most practical cases.

Magnetic modification of grid characteristic.

The upper part of the grid characteristic depends mainly on the ratio in which the space-current is divided betweed grid and anode.

That there is another factor controlling this ratio, additional to the geometrical dispositions, is shown by the difference between C.A.T.14 and C.A.T.12.

In these two types the relative positions of filament wire, grid structure, and anode, differ very little, and yet the grid current is proportionately appreciably different in C.A.T.12.

The further factor seems to be the magnetic field of the filament heating-current, which is some 71 amperes per limb in C.A.T.12, and 56 amperes in C.A.T.14. The influence of this does not extend very far out, because in C.A.T.10 with the same 71 amperes filament placed only some 30 % further from the grid the current ratio falls to the same value as in C.A.T.14.

This effect has not been studied fundamentally in terms of the motion of the electrons; still there is some further experimental evidence about it. When oscillograms are taken with the filaments heated by 50-cycle alternating-current—though this has been done only with another type, C.A.T.6—the grid current is found to be strongly modulated at 100 and 200 cycles, having two maxima and one minimum in each half cycle of the heating current.

Hence even with d.c. heating we should be led to expect different ratios of grid current to anode current if the filament heating-current is different, as it is between C.A.T.12 and C.A.T.14.

This effect must also have some influence on the output modulation, or "hum," produced when amplifier filaments are heated by alternating current. If there is a grid-leak, as in Class "C" anode-modulated, there will be grid modulation. Again, whenever the grid current is comparable with the anode current the latter will be modulated by subtraction of the grid current from the total space-current. Finally, there may be direct modulation of the space-current itself. Where the resultant hum is small, it is possible that one type of modulation may be opposing the others.

In an experimental version of C.A.T.6 which had a three-phase filament system, even "static" oscillograms, i.e. these taken with fixed grid and anode voltage, showed very complicated wave-forms, consisting mainly of triple-multiple harmonics—300, 600, etc., cycles. The three-phase arrangement could not be expected to eliminate such harmonics, and it is found that a pair of standard single-phase valves with filaments heated in quadrature by Scott-connected transformers and eliminating both 100- and 300-cycle components gives a much lower level of hum.

FLASH-ARC BREAKDOWNS (ROCKY POINT EFFECT)

The spontaneous breakdown of the vacuum insulation leading to a complete short-circuit of the valve by a vacuum arc, and occurring after a time-lag of anything up to some thousands of hours, was described to this Institution some five years ago.* It was felt at that time that, although the initiation of the discharge was not understood, enough was known about its later stages to enable breakdowns in operation to be made so rare as to be negligible.

A residue of doubt whether this would be possible for larger valves was already being dispelled, although it was known that the same degree of protection as for smaller valves could not be obtained on the circuit side.

These tentative conclusions have been shown by the experience of later years to have been sound, in that a progressive increase in anode voltage up to 18 or 20 kV for the later types of valves has resulted in little or no trouble in six stations which have been in operation for one or two years, using two different types of valves.

The establishment of this later improvement has resulted mainly from a general increase in the smallest clearance between the grid and anode systems. This increase was adopted in valves intended for the higher voltages, after it had been found by direct comparison that an increase from 9 mm. to 25 mm. in the C.A.T.6 class of valve raised the permissible overvoltage on a short test by more than 50 % above its normal value for the smaller clearance.

Investigation on the lines of the previous study showed that the way in which increase of clearance reduces the chance of breakdown is not altogether simple.

By using a movable anode in the form of a copper disc mounted on a metal "bellows" opposite to a flat-headed loop of 1 mm. tungsten wire as cathode, two things were established.

First, as to the voltage required to produce a discharge with a short time-lag, there was the somewhat surprising result that with the electrodes in anything approaching their final state it was unusual for a reduction in clearance from 12 mm. to 3 mm. to produce any notable fall in the discharge voltage. This is illustrated in the upper pair

* See Reference (3).

of curves in Fig. 16. Here the surface field in kV per cm. on the side of the cathode loop facing the anode is shown for each discharge point.

The progressive increase of field towards the smaller spacings where a discharge should be easier to establish makes it seem unlikely that breakdown is any simple consequence of the field, high though that is. The results shown by Mason* for smaller spacings from 1·2 mm. downwards, agree better with our general experience than his stated conclusions would imply. His later points show a similar rise in field.

Anderson,† however, has published results generally similar to ours.

The points appear in pairs because the observations, starting from the largest spacing and returning one step back from the smallest, were taken alternately with a voltage pulsating at 700 kilocycles between zero and the value shown, and with a continuous voltage. The small difference in the run of the two sets of points shows that

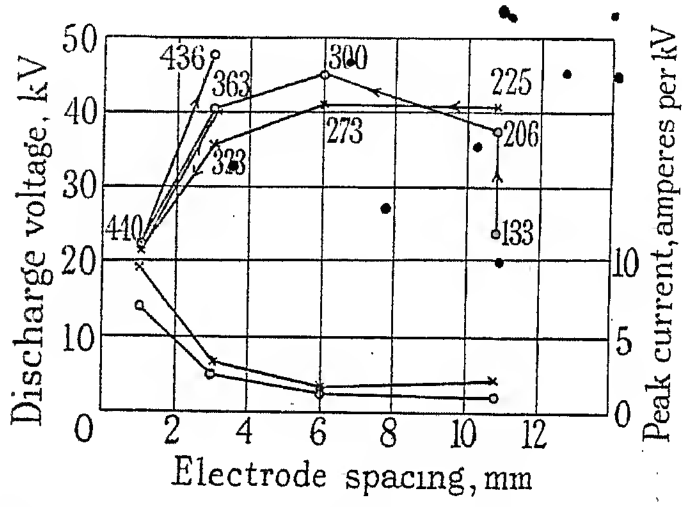


Fig. 16.—Flash-arc (Rocky Point) discharges in experimental tube with variable electrode-spacing.

Upper curves. Discharge voltage.
Lower curves. Peak current in discharge.
Points ⊙. Voltage pulsating at 700 kc.
Points ×. Voltage continuous.

the time required to build up conditions for a breakdown is very short.

Examination of the currents passing in the discharges —which have not so far been recorded by other investigators—throws some further light on what is happening.

The lower pair of curves show the peak value of the discharge current expressed in amperes per kilovolt. The theoretical value for an undamped discharge of the circuit used, 0·0002 μF and 4·5 μH is 7 amperes per kV and the observed peaks fall below this for the larger spacings, so much so that at 6 mm. or over at least nine-tenths of the initial energy of the condenser is used in building up the arc. Even so, in this particular experiment the current readings were higher than usual at the larger spacings.

Evidently the important point is that increase of spacing reduces the chance of a complete breakdown.

Nevertheless, there are other conditions to be satisfied, for if, as in Fig. 16, the electrodes were in a state where the general level of discharge voltage was below the maximum, change of spacing made much less difference to the currents, and so little or no advantage from the increased spacing remained.

However, the satisfactory operating experience shows that such conditions do not occur in finished valves.

The view that the presence of residual gas at relatively high pressures has no influence on the breakdown has been supported in operating experience. Considerable numbers of valves have been allowed to soften in operation up to pressures of the order of 5×10^{-4} mm. without any flash-arc breakdowns being reported.

The main principle on the circuit side of not permitting too much discharge energy to be too rapidly and continuously available still stands.

OPERATING CONDITIONS

About the operating conditions for high-power valves within their stated ratings there is little to be said. The need for constancy of filament supply voltage, if the proper average life is to be attained, is now well understood. For switching on the filaments and applying the anode potential, certain recommendations are made.

In the case of the filaments, the voltage should be applied in increasing steps over a period of about 30 seconds. The process is necessarily slow for two reasons. First, when the filament is cold its resistance is low, and the current it would take from a well-regulated supply at full voltage, e.g. a transformer tapping which happens to suit, might be 10 times the working value. The magnetic forces would thus be increased 100 times, and magnetic distortion would be unnecessarily encouraged, apart from possible catastrophic action on the initially brittle filament. Secondly, the temperature can overshoot the working value locally if there is sufficient local increase above the normal resistance per unit length, because of the local concentration of voltage in any region whose temperature, and therefore resistance, is rising more rapidly than elsewhere. The natural instability of the filament in this respect is thus exaggerated, and all filaments being affected more or less alike, the result may be simply that the average life is reduced without the reason being at all obvious. It is therefore recommended that for the first 10 seconds the filament current should not exceed 70 % of the working value; for this the applied voltage will have to be only some 7 % of the normal. After this, the voltage may be increased fairly rapidly, but so that the current never exceeds 130 % of the normal. The final voltage regulation has to be performed some minutes later when the leads, etc., will have reached a steady temperature.

As regards the anode potential, after any interruption during normal operation this may be switched on at a maximum of 70 % of the normal, and then after 2 seconds increased in one step to the full value.

For new valves, or valves which have been out of commission for some time, it is recommended that the initial voltage should be 5 000 for 10 minutes. This is followed by a gradual increase to the full value in not less than 20 minutes.

The cooling water must be pure enough to keep the anode free from serious deposits without requiring inconveniently frequent cleaning. For this it is recommended that the total dissolved solids shall not exceed 15 parts per 100 000, nor the solids precipitated on

* See Reference (13).

† *Ibid.*, (14).

boiling 4 parts per 100 000, nor the conductivity 300 reciprocal megohms per cm. cube. These are limiting values; purer water is better.

LIFE

The high standard of reliability demanded of transmitting valves to-day has already been referred to. Premature failures are to be avoided, and the failure zone restricted to a reasonable statistical percentage of the average life. A long average life is also desirable. Some idea of the standard achieved may be obtained from the overall average life of all reported failures of all types of cooled-anode valves. This has increased from 4 700 hours in 1932, to 6 400 hours in 1936.

There are many possible causes of failure, but filament burn-out is the only really fundamental cause. It may be delayed but cannot be prevented. The maximum life any valve can have is therefore the life of its filament, and we shall first consider the various factors which affect the life of a filament of pure tungsten, operating at a temperature of about 2 500° K. Filament failure is due to gradual wastage by evaporation, and eventual overheating of the thinnest point. It has been found, by examination of large numbers of burnt-out filaments, that failure occurs when the diameter is reduced by 10 % by evaporation. This rule holds whatever the initial diameter, and was first enunciated at the American General Electric Co.'s laboratories, for lamp filaments of 0·1 mm. diameter or less.* The wastage of various filaments of different original diameters between 0·82 and 1·33 mm. is shown in Fig. 17. There is a considerable length over which the wastage is uniform, indicating the region of uniform temperature. The ends show practically no wastage; this is due to cooling by the supports, and Fig. 17 also shows the cooling effect of the bracers. Evaporation appears to proceed normally until the diameter is reduced by about 10 % over a considerable proportion of the length; instability then sets in, and the temperature of a short length increases rapidly. Once started the effect is cumulative, and burn out follows quickly. This point is usually, but not always, the expected hottest point of the filament. The 10 % reduction in diameter applies for wire sizes from less than 0·1 mm. to more than 1 mm., and holds throughout the operating range of temperatures.

The life of a tungsten filament is therefore directly proportional to its diameter for the same temperature, but as the heating current varies as the 3/2 power of the diameter, economic and other considerations (e.g. end-cooling and magnetron effect) preclude very long lives being obtained simply by using large diameter wires.

Knowing that a filament will burn out when evaporation reduces its diameter to 90 % of its original value, we can readily and accurately calculate its life. Early life estimations for cooled-anode valve filaments using tungsten evaporation figures of Jones and Langmuir.† gave a theoretical life of about one-half the observed average. More recent simultaneous determinations of the emission and rate of evaporation of tungsten by Reimann, using samples of tungsten from the same source as our filaments, show Jones and Langmuir's figures to be high by a factor of about 2, and the estimated life using Reimann's results is in excellent agreement with the actual lives obtained.*

Glass valves in general give lives of about one-half the theoretical. This is probably the result of a variety of causes, the most important of which is sputtering of the filament due to the fact that the vacuum in glass valves is less perfect than in water-cooled valves. Another contributory factor is the operation of batches of glass valves at a common filament voltage, the exact voltage

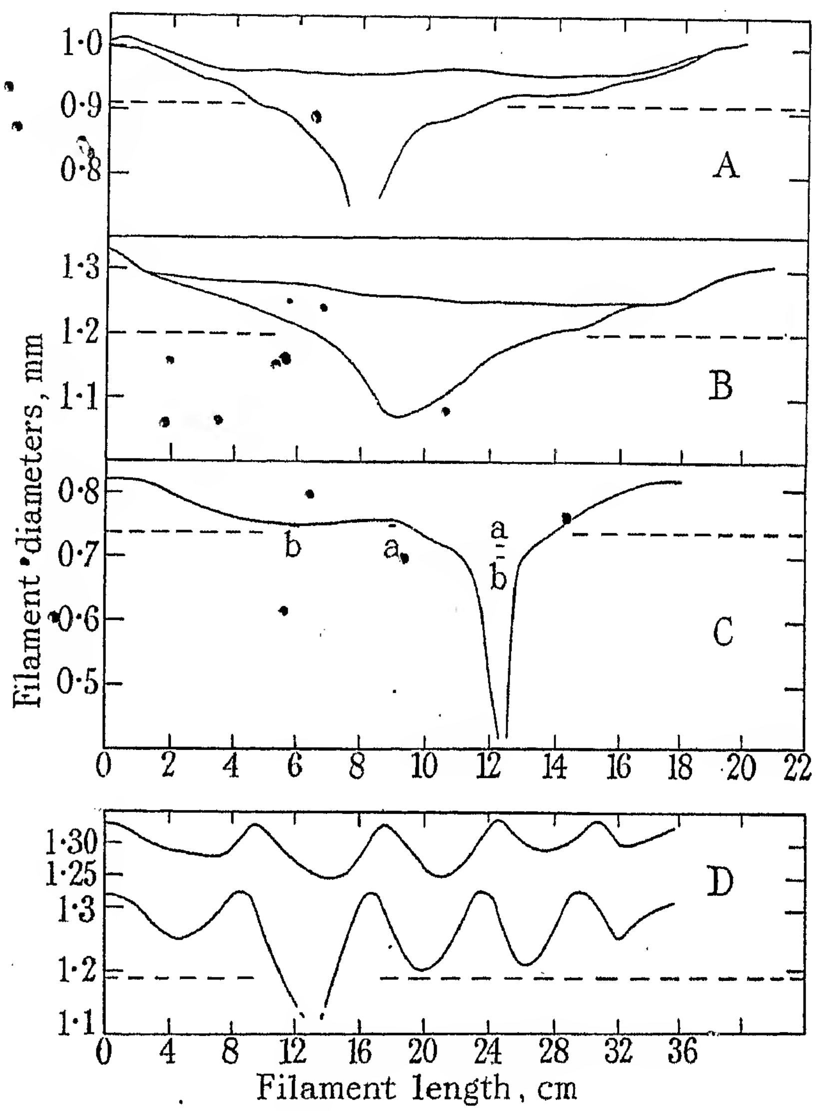


Fig. 17.—Reduction in filament diameter through wastage in operation.

A. Valve type C.A.R.2; 6 335 hours (overburnt about 5 %). Both limbs shown, one only burnt out.
B. Valve type C.A.R.4 (V.T.36); 19 400 hours. Both limbs shown, one not quite burnt out.
C. Valve type C.A.T.6; 10 817 hours. One limb of one loop shown in full.
  a. Measurements at points on companion limb of this loop.
  b. Measurements at points on companion loop, wastages on both limbs equal.
D. Valve type C.A.T.10, early specimen with too many bracers. One of 3 burnt-out limbs shown, and one of 3 companion limbs of other polarity.

Broken lines show levels for 10 % loss in diameter.

being decided by the worst emitter, as distinct from the individual adjustment to marked volts for cooled-anode valves.

As already described, it is the general practice to operate the filaments of cooled-anode valves at a temperature just sufficiently high to satisfy the emission demands of the circuit. Filaments are therefore rated on an emission basis, individual valves being stamped with the filament voltage required to produce a certain

* See Reference (15).

† *Ibid.*, (5).

* See References (5) and (16).

emission (marked voltage). A 5 % increase in this voltage increases the emission by 50 %, but reduces the life to one-half. This rapid variation of life with filament temperature necessitates the use of sub-standard instruments for the adjustment of filament voltage if the maximum life is to be obtained.

putting a resistance equal to one-third that of the active filament in series and maintaining the whole at constant voltage. The resistance of the leads and of the cool ends therefore gives some compensation.

Constant filament-current operation cannot be tolerated, as in that case temperature and emission increase

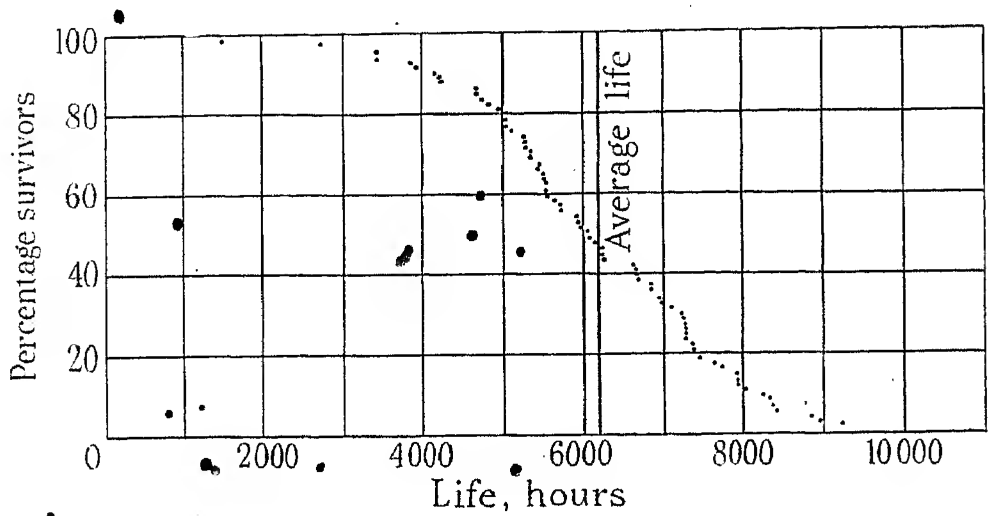


Fig. 18.—Survivor curve for 74 valves, type C.A.T.6, operated at "marked volts" in B.B.C. transmitters.
Failures for filament burn-out only.

Fig. 18 shows a survivor curve for 74 C.A.T.6 valves operated at marked volts in B.B.C. Regional transmitters. This curve is for filament burn-out failures only, and is typical of cooled-anode valves operated at marked volts. Some 60 % of the failures occur within ± 20 % of the average life, a few per cent of the valves fail at half the average life, and a few per cent survive to almost twice the average. The average life agrees very closely with the calculated value.

It may be asked whether multiple-filament valves last as long as the equivalent number of smaller valves. The answer is that apparently they do. This would only be so if the behaviour of all the limbs were very nearly equal. For although the parallel connection of unequal limbs must have some stabilizing effect in that initially thicker limbs will run hotter until the consequent more rapid evaporation has produced equality of diameter, yet initial equality is necessary since one-half of the limbs is in series with the other half. The limbs of each system are therefore carefully matched for diameter, and also all the wires are drawn with the same smooth compact surface, to equalize their thermal radiation properties. This last point is, as we have seen, of great importance.

It has been found experimentally that for valves operated at constant filament voltage the emission falls gradually during life. This is to be expected, since at constant voltage, apart from any change in surface condition, the temperature falls slightly during life, and of course there is the reduction in emitting area due to wastage. Emission measurements on long-life valves have shown that the drop in emission is rather greater than would be expected from the above considerations. The difference is due to the fact that the filament becomes less brightly polished during life, with a consequent further reduction in temperature and emission. If the surface condition of the filament remained uniform constant emission during life could be approached by

rapidly, and the life is only about one-fifth of the constant-voltage life. Constant emission is the ideal method of operation, and so far this has only been attained by increasing the filament voltage during life according to a predetermined schedule based on the results of emission tests on long-life valves. The survivor curve obtained

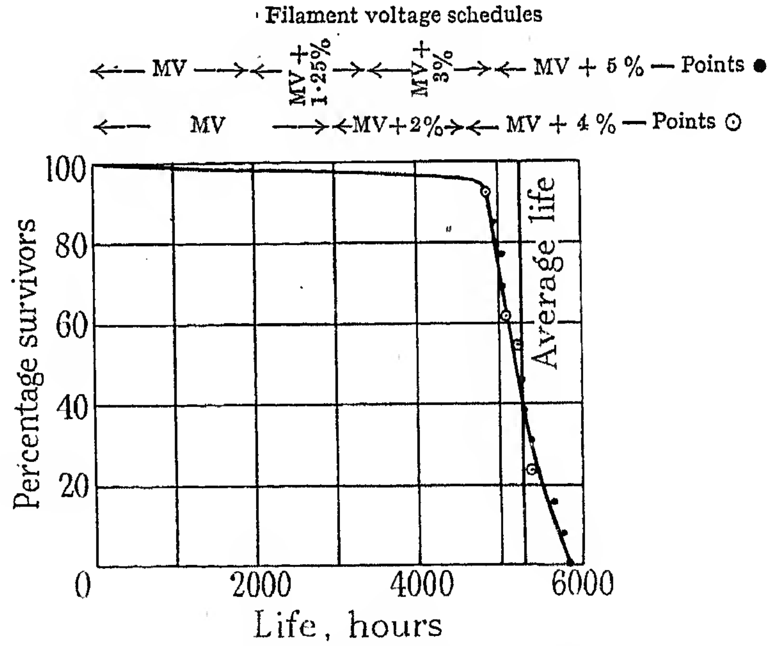


Fig. 19.—Survivor curve for 13 valves, type C.A.T.6, operated under conditions approaching constancy of emission during life in the B.B.C. London Regional transmitter.

The filament voltage schedules indicated are approximate.
Failures for filament burn-out only.
MV = Marked volts.

by such a method of operation is shown in Fig. 19, which is for a batch of C.A.T.6 valves operated in the London Regional transmitter. Comparison with Fig. 18 will show that the curve is much steeper, i.e. the spread is much reduced, and the extra-long-life valves are eliminated. The extreme sharpness of the shoulder is

partly accounted for by the fact that an increment of filament voltage comes just before this point. The smallness of the overall spread is a verification of the accuracy of the original emission test and its extrapolation.

The average life under these conditions is reduced by about 15 %, but even so the practice of constant emission operation will tend to grow, since with constant voltage the filament must be over-run originally if it is to have sufficient emission towards the end of its life.

Table 1

VALVE TYPE, C.A.T.14.

Record of all C.A.T.14 valves used at the Beromünster Transmitter up to 31st December, 1937.

Serial No.	Life, hours	S = Survivor F = Failure	Cause of failure.
13	8 049	S	—
14	4 724	S	—
15	8 014	S	—
16	4 701	S	—

Record of all C.A.T.14 valves used at the B.B.C. Droitwich Transmitter up to 31st December, 1937.

1	7 228	S	—
2	3 127	F	Partly F.B.O.
3	9 483	F	F.B.O.
4	7 660	S	—
5	12 443	F	Leaky bellows*
8	1 421	F	Leak in foot tube*
9	1 896	F	Leaky bellows*
9A	5 162	S	—
10	5 569	S	—
11	8 985	F	F.B.O.
12	1 519	S	—
25	254	F	Leak in anode soldering
26	2 260	S	—
27	1 749	S	—
29	1 864	S	—
46	2 017	S	—
64	1 312	S	—
68	255	S	—
69	211	S	—

Record of all C.A.T.14 valves used at the Motala Transmitter up to 31st December, 1937

17	10 885	S	—
18	7 249	F	Blue glow
19	4 162	S	—
20	10 004	S	—
21	10 743	S	—
22	1 739	S	—
23	190	S	—

* These valves were manufactured before the trouble with leaky bellows had had time to develop in C.A.T.10 type valves at Warsaw and Rugby.

Filament life can be considerably reduced by over-rapid switching, but such failures can be distinguished from normal failures by the nature of the break. Normal failures show a gradual taper on either side of the actual burn-out, while for filaments which have been over-switched the open circuit is more in the nature of a break than a burn-out, and in severe cases the filament may be distorted through the magnetic forces.

The absence of locally-accelerated evaporation in such cases seems to show that the real cause of the instability may be a local increase in resistivity, due to some internal change, rather than an increase in resistance due to reduction in diameter. It is only when the onset of instability is slower, as in the normal case, that there is time for the usual tapering towards the point of failure to develop. That the cause of instability is not the general loss of diameter according to the 10 % rule is also shown by the fact that, if the metal is removed rapidly by sputtering in a poor vacuum, the filament remains stable even when the diameter has been reduced by much more than 10 %. However, in valves as we know them

Table 2

VALVE TYPES MENTIONED IN THE PAPER

Type	Filament Volts (nominal)	Filament Amperes (nominal)	Filament Emission (90 % saturated) amperes	Max. Anode* voltage, d.c.	Max. Anode dissipation, kW	Normal wave-length (L=long S=short)
High μ Triodes						
VT26	22	41·5	5·5	12 000	10	L
CAT6	18/20	75	10	12 000	12	L
CAT10	30	220	35	15 000	50	L
CAT12	30	220	35	18 000	75	L
CAT14	32·5	460	100	20 000	150	L
CAT17	32·5	460	100	15 000	150	S
CAT19 (E8 30)	31·5	660	150	20 000	150	L
Low μ Triodes						
CAM3	17	70	3/7	12 000	12	L
CAM4	20	75	10	15 000	16	L
CAM5	28	325	22·5	15 000	60	L
CAM6	20	190	14	15 000	30	L
CAT12A	30	220	35	18 000	75	L
Rectifiers						
CAR2	18/20	50	4	15 000	5	
CAR4	18/20	75	7	15 000	6	
CAR6	18/20	120	10/20	20 000	20	

* Subject to certain restrictions as to circuit protection against flash-arcs.

the 10 % rule is still the expression of a reliable symptom of distress, even though it does not directly represent the actual disease.

The great majority of valves fail through filament burn-out, and only a small percentage through other causes. The effect of other failures on the survivor curve is to flatten the top bend, and hence to reduce the average life. For an established type, the percentage of other failures is very small, and the overall average life approaches the theoretical filament life.

For the largest valves, operation has not yet proceeded far enough to provide data for a survivor curve, but Table 1 shows the complete record of the three stations in which these valves have been in use longest.

Inspection of the serial numbers of the valves suffices

to show that the occurrence at Droitwich of the majority of the failures for causes other than filament burn-outs is due to the fact that that transmitter was the pioneer in the adoption of the C.A.T.14 type.

In conclusion, the authors desire to tender their acknowledgments to Marconi's Wireless Telegraph Co., Ltd., and the General Electric Co., Ltd., on whose behalf the work described was done. They also wish to thank the Post Office, the British Broadcasting Corporation, and other operating authorities, and especially the members of the staffs of the various transmitting stations, whose reports of valve performance, compiled in great detail and at frequent intervals, have been most helpful and encouraging throughout the development of high-power valves.

REFERENCES

(1) W. J. Picken: *Journal I.E.E.*, 1927, vol. 65, p. 791.

(2) R. le Rossignol and E. W. Hall: *G.E.C. Journal*, 1936, vol. 7, p. 176; and *Marconi Review*, 1936, No. 61, p. 6.

(3) B. S. Gossling: *Journal I.E.E.*, 1932, vol. 71, p. 429.

(4) J. Bell: *Proceedings of the Royal Society*, A, 1933, vol. 141, p. 641.

(5) H. A. Jones and I. Langmuir: *General Electric Review*, 1927, vol. 30, p. 310.

(6) R. A. Fisher: "Statistical Methods for Research Workers," [Edinburgh and London] 1936, p. 137.

(7) J. W. Avery and C. J. Smithells: *Proceedings of the Physical Society*, 1926, vol. 39, p. 85.

(8) A. G. Worthing: *Journal of the Franklin Institute*, 1922, vol. 194, p. 527; also W. E. Forsythe and A. G. Worthing: *Astrophysical Journal*, 1925, vol. 61, p. 146.

(9) W. Schottky: *Physikalische Zeitschrift*, 1914, vol. 15, p. 872.

(10) N. A. de Bruyne: *Proceedings of the Royal Society*, A, 1928, vol. 120, p. 423.

(11) B. S. Gossling: *Journal I.E.E.*, 1920, vol. 58, p. 294.

(12) B. S. Gossling [quoted by A. L. Reimann: "Thermionic Emission," London, 1934, p. 59].

(13) R. C. Mason: *Physical Review*, 1937, vol. 52, p. 126.

(14) H. W. Anderson: *Electrical Engineering*, 1935, vol. 54, p. 1315.

(15) S. Dushman: *General Electric Review*, 1915, vol. 18, p. 156.

(16) A. L. Reimann: *Philosophical Magazine*, 1938, vol. 25, p. 834.

(17) A. C. Bartlett: *Experimental Wireless and Wireless Engineer*, 1927, vol. 4, p. 430.

DISCUSSION BEFORE THE WIRELESS SECTION, 30TH MARCH, 1938

Mr. H. S. Walker: The early cooled-anode valves frequently went "soft" after a few hundred hours of operation; and therefore in 1930 the B.B.C. fitted in their regional transmitters a two-range microammeter which could be used for the measurement of grid current when the transmitter was operating, or, when the shunt was disconnected, for measuring the backlash current. The gas tests described by the authors were used originally by us to detect when valves were going soft, so that they could be removed before they caused an interruption in the service. Nowadays, however, as the vacuum remains nearly constant, there is little use for this test. Nevertheless, since 1930 the engineering staff of the B.B.C. have taken 38 500 gas-test readings.

These readings, particularly the ones on C.A.T.14 valves at Droitwich, have revealed a new phenomenon. Shortly after Droitwich was opened in June, 1934, one of the C.A.T.14 valves, No. 9*a*, showed a backlash current of about 400 microamperes as compared with the value of 150 microamperes at the normal anode current of about 2 amperes. The organization which the authors represent were informed of this, and proceeded to repump the valve. When it was returned to service a normal backlash figure was obtained. Some months later, however, the backlash figure began again to increase, and after about another 1 000 hours a figure of 750 microamperes was obtained. The valve was examined for leakage but none was apparent, and it was again repumped. After about another 1 000 hours the backlash increased fairly suddenly to the rather large figure of 2 500 microamperes, and finally to 5 000 microamperes. So great was this figure that, if it had been due to softness, the valve would have shown a blue glow, which it did not. The valve in fact worked perfectly normally and was therefore kept in circuit; after a week the backlash had fallen to some 400 microamperes, at which figure it has remained. Since that time the valve has been in operation for about another 2 000 hours.

Recently another valve, No. 83, has shown similar symptoms, and, as they could be reproduced without application of the anode voltage, a leakage in the circuit or across the valve seemed to be a possible cause; but practical tests did not confirm this suggestion. I think that the cause of this apparent backlash current must be some form of primary emission from the grid, due to heating of the grid or radiation from the filament. Since pure tungsten has an affinity for thorium, it is possible that during pumping operations a small quantity of thorium or sodium was taken up by the grid. Various causes, such as sudden changes of temperature at the grid, might result in the thorium diffusing to the surface, and there producing an emission which might account for the phenomenon I have described. Such irregularities of emission are not unknown in valves fitted with thoriated-tungsten filaments. It is reasonable to suppose that, if this explanation is the correct one, the two repumping operations which the authors' organization carried out were unnecessary. I should be interested to have their observations on this point.

Reliability of operation and freedom from breakage are more important in broadcast transmissions, at least as far as the B.B.C. is concerned, than in any other service in which valves are used. At the same time the distortion factor of a transmitter must be kept down to a very small value: a figure of about 4 % at 80 % modulation is the most usual. This demands a much more nearly linear characteristic in the valve than is required for telegraphic or commercial telephonic use, and, since this must be

maintained through life, a schedule of gradually increasing filament voltage is applied to B.B.C. stations. Fig. 19 shows one of the schedules adopted, which applies to C.A.T.6 valves in B.B.C. Regional transmitters. We have found by practice that 1·15 amperes per valve is the maximum we can work at and maintain linearity with reasonable economy of filament, and it is on this basis that the schedule of increasing voltages shown in Fig. 19 has been built up. Under these conditions C.A.T.6 valves in B.B.C. Regional transmitters averaged 5 816 hours during 1937, taking all failures into account. (The slightly higher figure quoted by the authors includes the filament burn-outs only.) If it were not for the stringent conditions of linearity demanded by our service, very much better figures could be obtained. We have heard of foreign stations with C.A.T.6 valves which have lasted for 10 000 hours, but the distortion must have been greater since the filaments were run at a lower temperature.

The authors state that the electrical conductivity of cooling water should not exceed 370 reciprocal megohms per cm. cube. While such water is doubtless quite safe from the valve point of view, it would give rise to all sorts of troubles in other parts of the equipment, particularly electrolysis down the water hose columns. A maximum safe figure is much more likely to be of the order of 100 reciprocal megohms per cm. cube. The water used by the B.B.C. is much purer, with a conductivity of the order of 30 reciprocal megohms per cm. cube.

Mr. S. R. B. Pennington: As indicated in the paper, we are considering adopting forced-air cooling for the external filament leads of new high-power cooled-anode valves, instead of water-cooling. This change should simplify the cooling circuits, but it may give a lower factor of safety.

This important question of cooling-circuit simplification has led to a consideration of the use of air-cooling for the anodes of larger valves. The largest size to which air-cooling has so far been applied has an anode-dissipation rating of about 5 kW and requires some 300 cu. ft. of air per minute for cooling purposes. These are not yet in commercial use, but an air-cooled version of the ultra-short-wave valve C.A.T.15 has been in service in the B.B.C. mobile television transmitter since May, 1937.

The authors refer to the difficulty of obtaining early life data for the larger valves: in this connection we have been fortunate in having the collaboration of the B.B.C., in that their progressive policy has enabled us to supply them with apparatus embodying many of the larger-type valves immediately they have reached the production stage. Examples are the C.A.T.14 valves at Droitwich, and the short-wave version of this type in the high-power short-wave transmitter recently installed at Daventry.

The short-wave C.A.T.14 valve has a separate circular grid seal, an anode dissipation of about 150 kW, and a filament emission of about 100 amperes. Although much work has been done, we have not yet determined the limiting wavelength at which the performance of this valve can still be considered satisfactory, i.e. the wavelength at which transit-time effects and the resultant grid-load call a halt. At 13 metres, however, the anode conversion efficiency still holds approximately to the long-wave value, although there is some indication of losses introduced by electron transit-time effects as the grid input has risen slightly above the general level at the longer wavelengths. With this valve operating in a 13-metre circuit as a modulated Class C amplifier at the normal input, a carrier output of 50 kW at an anode efficiency of about 70 % is normal.

Finally, in their schedule of operating conditions the authors mention the precautions essential to good valve life. To these I would like to add the suggestion that station authorities should see that all spare valves are periodically tested under normal working conditions, so that damage or defects occurring during storage may be detected at an early date and a known good stock held.

Mr. B. N. MacLarty: I am glad to learn that it may be possible in the near future to adopt air-cooling for the anodes of larger valves. Such a practice is more feasible now than it was a few years ago, owing to the introduction of high-efficiency systems of modulation in which the valves are worked at much less than their rated anode dissipation. I can, however, visualize some difficulties in connection with the introduction of the air to the valve and its removal. Will it ever be possible to air-cool a valve of the C.A.T.14 size? I am particularly concerned regarding this matter, because the cost of the cooling system in a high-power transmitter is a considerable part of the total cost of the station, and I think it is now advisable to consider either working at higher water temperatures or adopting some other method of cooling.

The question of the water cooling of filament and grid seals is also very important. Owing to the small volume and low velocity of the water passing through these seals we get trouble due to the settlement of fine sediment inside the cooling labyrinth, and it will be an improvement if future high-power valves have their seals cooled by air.

The possible trouble mentioned by Mr. Pennington, regarding the failure of the air supply in an air-cooling system, can be overcome by adopting a principle similar to that which we have adopted on water-cooling systems, namely two pumps in parallel either of which is capable of dealing with the total load.

The fact that the magnetic field due to the filament-heating current can sensibly modulate grid current, is a matter of interest, especially as we are nowadays being pressed to adopt alternating current for heating filaments. The authors' comments on this matter indicate that great care is necessary in the design of valves in which alternating current is to be used for heating the filaments.

Although valves are in use having 3-phase filaments which give remarkably low noise-levels, it appears that their success in this respect may be to some extent fortuitous. The authors mention that valves with single-phase filaments connected by Scott transformers give a lower hum level than 3-phase valves. This may apply to the particular valves tested by them, but I am not convinced that the subject has been sufficiently investigated. Are the authors aware that a remarkably low hum level has been obtained from a single C.A.M.5 valve, working as a modulator and heated by 50-cycle alternating current?

Mr. L. Grinstead: I should like to know what the authors' experiences are with the use of tungsten for grid-building purposes, as I have found in general that tungsten grids are much more prone to secondary emis-

sion than are molybdenum grids. An interesting point is referred to on page 183 in connection with the photo-electric properties of molybdenum and tungsten. Is it possible that these photo-electric effects have some bearing on the increased secondary emission observed from tungsten?

The authors speak of the possibility of employing a grid lead-out in the form of a metal cylinder sealed between two sections of the glass envelope; this no doubt makes a very good attachment to the grid itself, but would it be so easy to make a physical connection from a high-frequency circuit to such a cylinder? I believe that a grid seal of this description would not show much advantage over two well-constructed side seals of more or less conventional type.

As regards this question of seals for grid and filament connections, valves have been made for some years with chrome-iron seals carrying quite high values of radio-frequency current, but usually these seals are made in the form of thin discs. No difficulty has been experienced with them, although the authors appear to have had unfavourable experience with chrome-iron seals.

In connection with Figs. 7(*a*) and 7(*b*), I notice that actual tests are made for values of emission up to approximately 10 % of full rating and that the authors have also plotted on these diagrams one or two points as additional observations for checking the extrapolation. Apparently a diode is used for the check values, and while this method disposes of the problem of power dissipation it does not eliminate the effect of space current on the distribution of filament temperature. Are these check observations taken by the intermittent method referred to early in the paper?

Finally, I should like to ask for a little more information concerning the authors' statement that the practice of constant-emission operation will tend to grow. It seems to me that while in theory it is desirable to have valves running under constant-emission conditions, fundamentally it is not of great importance provided there is enough emission initially to meet circuit requirements and good valve lives are obtained. In the results shown in Figs. 18 and 19 it appears that substantially constant-emission operation is obtained at the expense of 15 % of average life, which I think is rather uneconomical from the user's point of view.

Mr. L. B. Turner: The development of the high-power valve marks, as far as we can guess, the end of the changes in the method of producing high-power high-frequency current. We have seen developed and discarded the spark transmitter giving damped trains, the rapid-spark modification giving an approximation to continuous-wave working, the Poulsen arc, and the various patterns of electromechanical alternators with and without subsequent frequency multiplication. All these were shown to be capable of producing an output of some hundreds of kilowatts; but all were relatively complicated and inflexible contrivances, and they have been set aside in favour of the monument of simplicity shown in Fig. 1. After explaining their empirical procedure, the authors say that "the further it is removed from the plane of trial and error by increasing insight into what is actually happening in the valve in manufacture and in operation, the more quickly will improvements be made and faults eliminated." A most satisfying feature of their work seems to me the thoroughness with which this principle has been acted upon.

Many interesting empirical discoveries and theoretical investigations were made by the authors: I want just to refer to one of each. First, who would have anticipated that the problems of water-cooling of the copper anode would prove to be seriously influenced by the streakiness of the electron bombardment owing to the focusing action of the grid wires (as described on page 181)! Second, in seeking to obtain uniformity of filament emission in different valves of a type, how elegant is the statistical analysis of Fig. 8, where a diagnosis is got from the axes of scatter in the target diagram of volts plotted against amperes for equal emission!

In triodes for transmission, as in those for reception, a long extent of sensible straightness of the characteristic is often desired: but, as far as I have been able to ascertain, the straightness obtained has been determined by accident rather than design. In Fig. 10, it seems that from C to B (and I do not understand why not also below C) the curved foot of the $\frac{3}{2}$-power space-charge law is modified by the magnetron cut-off effect; and I think this effect must be a straightening one, since it becomes less apparent as the anode potential rises. From B to A we have the $\frac{3}{2}$-power law, but over a limited range which is itself fairly straight; and above A, the continued upward concavity of the $\frac{3}{2}$-power law is countered by incipient saturation of the non-uniform filament, tempered by the telescoped Schottky effect described on page 190. As the happy result of all those actions the characteristic is said to be straight from C to D—say from 1A to 4A when the saturation current is 5A. Again I venture to ask; are the effects thus analysed consciously cultivated and balanced as part of the design?

With reference to Fig. 11 it is explained how the full-emission characteristic may be calculated from the curve observed with an under-heated filament. Although I think the theoretical basis of this procedure must be right, I cannot follow the argument on page 191. I suspect there is a logical hiatus; for the validity of the construction must surely depend on the log/log plotting in Fig. 11, and this is not referred to in the argument on page 191.

Four brief points in conclusion: (i) Will the authors say what, if any, is the distinction (on page 182) between "equilibrium pressure" and the actual pressure in the valve? (ii) On page 185 "heating current H leaving the positive end of the filament" is, I think, a misprint for "entering the positive end"; and, if so, the words "local temperature" four lines lower should apparently read "temperature at the negative end." (iii) Can Fig. 1 be supplemented by a statement showing the linear dimensions of the C.A.T.14 valve and giving some rough indication of the cost? (iv) What happens to the 2–3 oz. of tungsten evaporated during the life of a large valve? Is it ionized by electron collision? Is it deposited on the grid or on the anode?

Mr. W. T. Gibson: I should like to give a short account of a valve made by the company with which I am associated, which shows how similar problems to those dealt with by the authors have been solved by rather different methods.

Plate 3

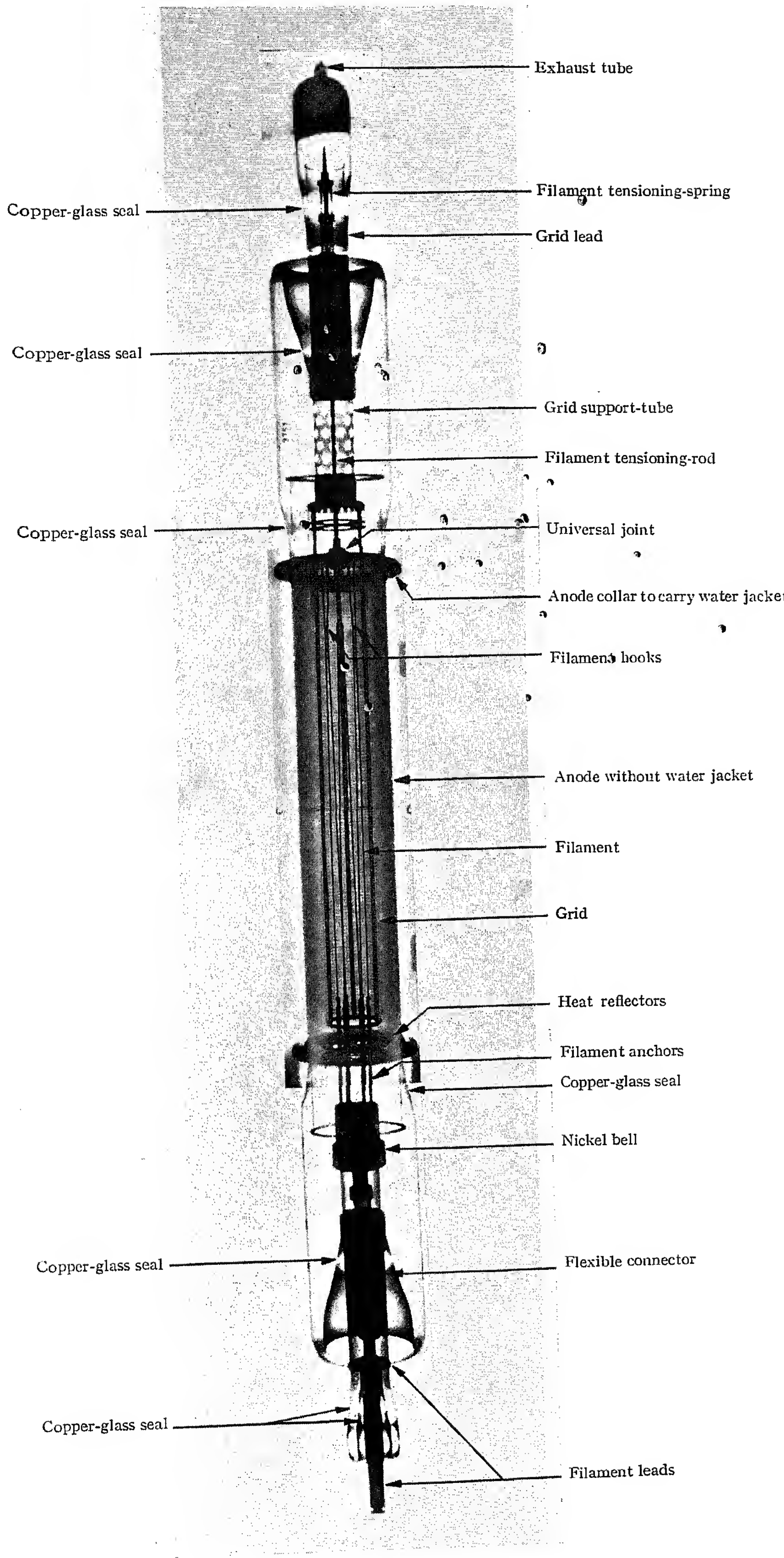


Fig. A

(Facing page 200.)

Plate 4

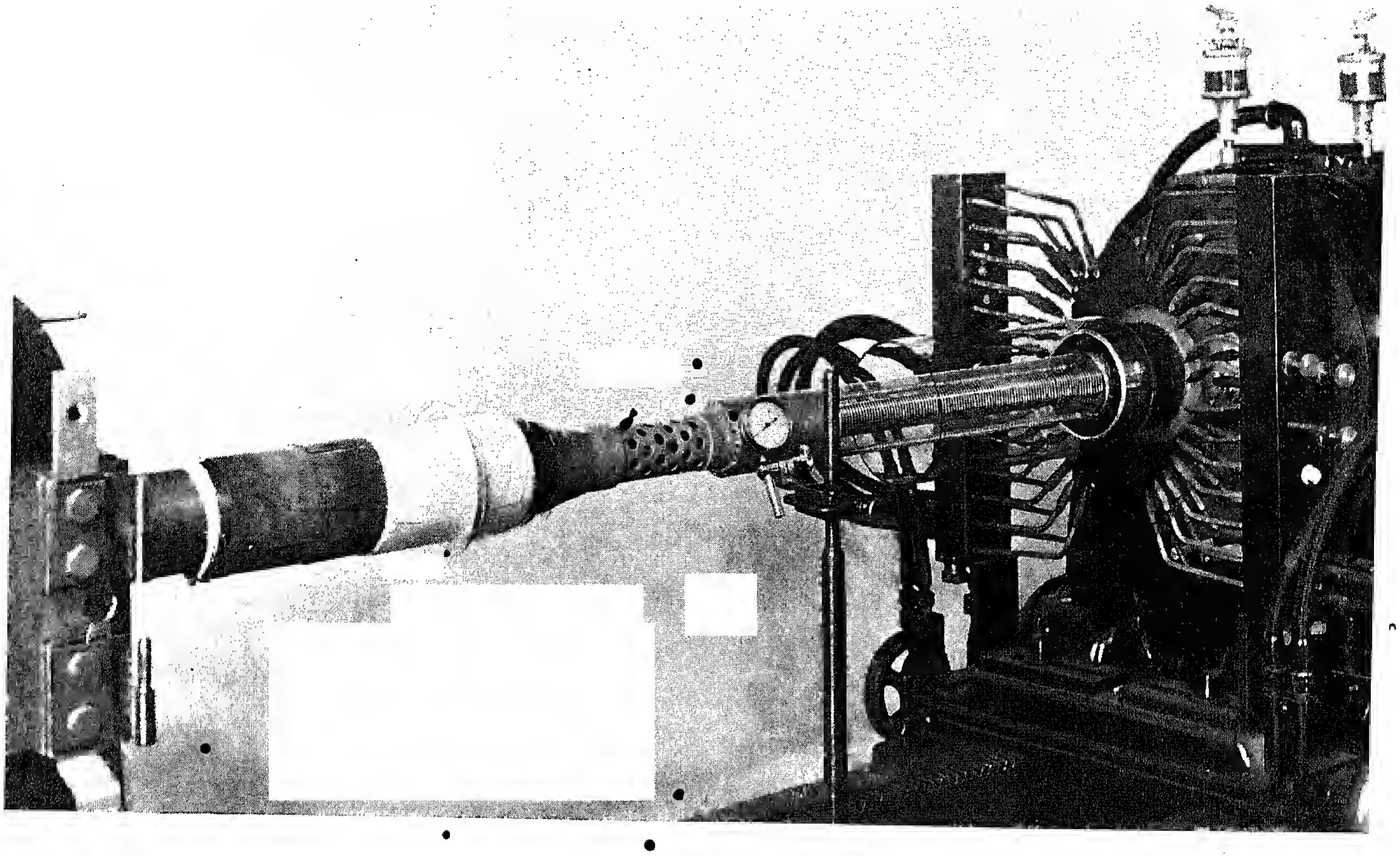


Fig. B

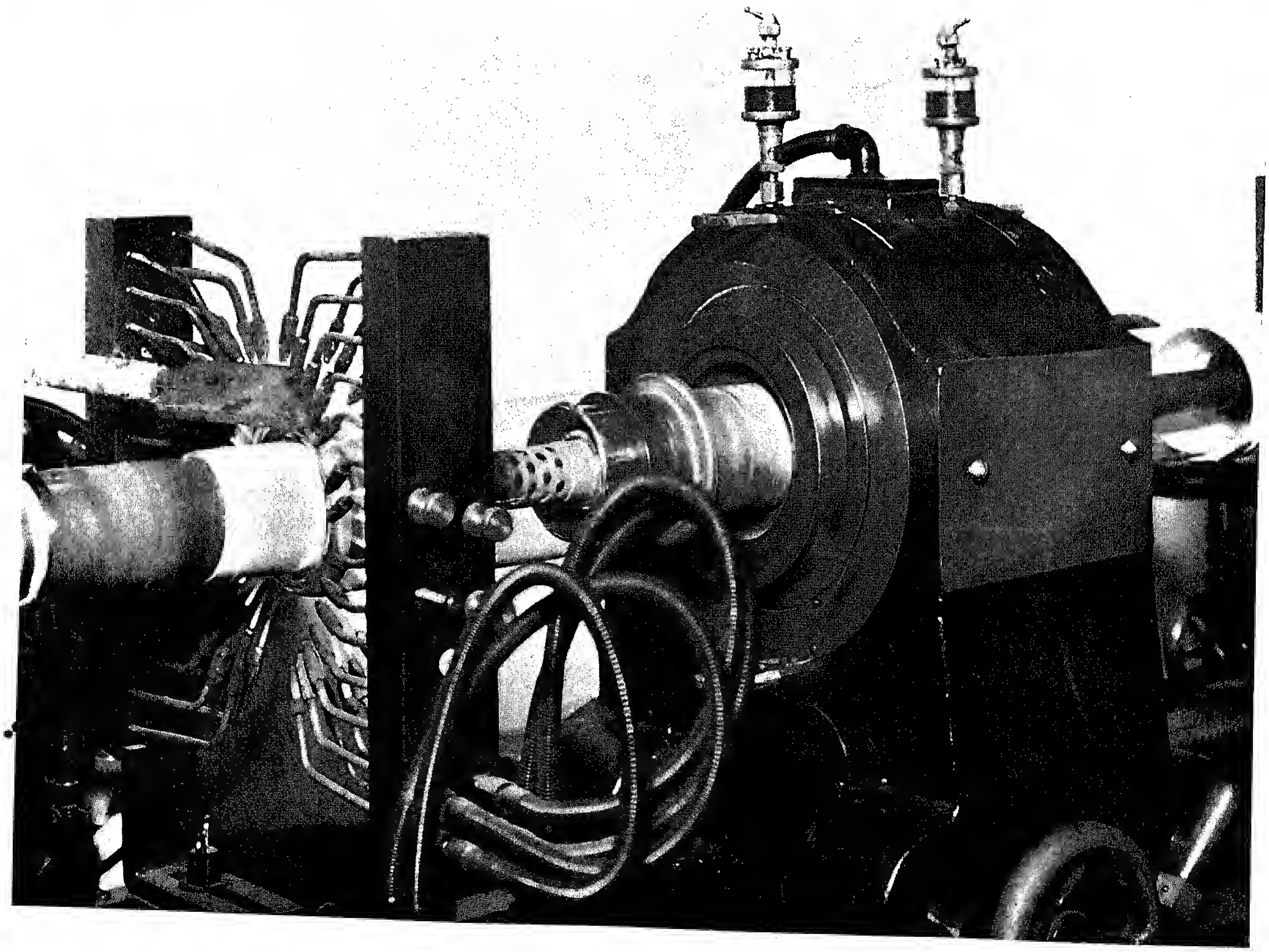


Fig. C

Some time ago we had the task of developing a valve, Type 4030, which was to have a useful emission of 45 amperes and to be suitable for operation on long or short waves. In view of past experience, it was decided to make it double-ended, and it was known that it would probably be required to operate with the filament terminals at the lower end. As a result, what we believe is a unique type of construction was adopted (see Fig. A, Plate 3, facing page 200).

The filament leads consist of two concentric copper tubes, joined to the filament stem by copper-to-glass seals, and there is a flexible connection made of copper cable in the inner lead to allow for relative expansion. The two filament leads are joined positively together inside the valve by means of a steatite insulator which separates them electrically. This insulator is located inside, and completely surrounded by, a highly polished nickel bell from which the six filament anchors project.

The filament consists of three hairpins of tungsten without any central support. The bights of the filaments are carried by hooks which are mounted on a ball-and-socket universal joint consisting of a tungsten ball engaging in a molybdenum socket carried by a molybdenum rod which passes through the grid stem, which is again a copper tube sealed to the glass. The rod passes through two silica insulators which occupy a cold portion of the tube, and is then pulled by a spring which is adjusted very accurately to the required tension.

The development of this valve was very greatly helped by the use of a glass-working lathe which we constructed some years ago. This lathe has a bed about 12 ft. long, three heads with special chucks, and two fire heads. The machine is of the very highest precision, equal to that of a high-class metal-working lathe.

As the valve has an axis of symmetry, it is possible to take full advantage of the precision of the lathe, and as an indication it may be stated that the grid is checked for truth with a dial gauge on the lathe immediately before being sealed in. The lining-up of the grid is shown in Fig. B (see Plate 4), and the sealing-in in Fig. C (see Plate 4). The filament is sealed into the opposite end, a tool being inserted through the centre of the filament stem to hold the assembly at this stage. The lathe is provided with an electric annealing oven which allows the complete annealing of the glass without disturbance of the geometrical relationships. When the valve has been removed from the lathe, the tool which holds the filament structure is withdrawn and the end of the filament lead closed by brazing-in a copper disc.

After the valve has been exhausted, the water jacket is soldered on. This water jacket is so constructed that the cold water enters at the middle and flows beneath the baffles, giving a thin film flowing at high velocity over the heated surfaces. The water is then collected from the two ends and taken to the outlet pipe. The water jacket is corrugated, to provide flexibility to compensate for the relative expansion of anode and jacket. The valve operates silently and with perfect safety on test up to 160 kW dead loss.

The precision obtainable by these methods has made it possible to produce valves of extremely high constancy and regularity of characteristics. For example, in a recent group under normal manufacturing conditions, 85 % of the valves had an anode current within $\pm$ 4 % of the rated value, and 85 % have filament volts and current within $\pm$ 1·5 % of the mean.

The connections to these valves are made through cast aluminium radiators which are jointed to the filament and grid leads. Ample cooling is provided by the natural circulation of air, forced air or other cooling being unnecessary. In order to give an idea of the factor of safety, I may say that during the pumping of the valve the anode is operated at 800° C. and no radiators are used on these electrodes. Connections of very small section are made to the electrodes, and no auxiliary cooling is employed even under these circumstances.

The importance of the contribution of photo-electric current to total gas current mentioned by the authors is clearly demonstrated in the testing of this type of valve, and Fig. D shows the frequency of occurrence of any given value of gas current among a large group of valves. It will be seen that the maximum frequency occurs at the minimum recorded value.

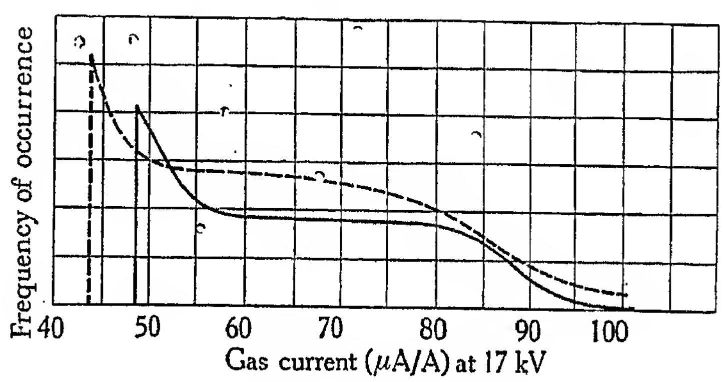


Fig. D

The method which we use for estimating the total emission is rather different from that described by the authors. We use Davisson power-emission paper, and make measurements of anode current up to about 10 amperes. On this paper the total-emission lines are absolutely straight, and the ratio between the filament watts at the required emission and at, say, 10 amperes emission is constant to within less than $\pm$ 1 % from valve to valve.

These valves are in use in a number of large stations, including the Daventry Empire Stations, and the following record of valve life of all valves in the Liblice station indicates the satisfactory nature of the performance:—

Valve serial Nos. 6032, 6192, 6031, 6054, 6006—7 854 hr. 15 min.; No. 6042—4 747 hr. 0 min.; No. 6140—3 107 hr. 15 min. All except the last-named were survivors.

Mr. J. Greig: I regret that, presumably on account of space limitations, it has not been possible to treat more fully the inter-relations between valve characteristics, circuit conditions, and linearity requirements.

I should like to comment on one or two points relating to the design of valves of higher powers for operation on short wavelengths.

The provision of multiple seals or ring seals for the carrying of heavy grid or screen currents, and the difficulty of obtaining uniform distribution of such currents, are referred to in the paper. This non-uniform distribution, resulting from the different effective inductances of the various current-paths within the valve, in relation

to the disposition of the external circuit, would appear to be to a large extent inevitable, and where the current is conveyed to the active portion of the grid by the grid supports themselves, some distortion of the structure due to unequal heating is to be expected. It would be interesting to know whether it might be considered desirable and practicable to by-pass the high-frequency currents from the grid supports by relatively flexible strip conductors more suited to the carrying of high-frequency currents, making contact with the grid as near as possible to its active portion where the temperature would, for the most part, be determined by radiation from the cathode and by grid energy dissipation.

The necessity for reducing to a minimum the inductance of the path between the grid seal and the active portion of the grid is well recognized, but the most inherently inaccessible electrode of the valve is the incandescent cathode, the true "earth" of the circuit, and it seems probable that the inductance of the cathode and its associated leads may not have a negligible effect at short wavelengths. It is likely that some of the loss of efficiency in short-wave circuits, in the region before transit-time effects become significant, may be due to the inductance of the cathode circuit. Certainly the difficulty of anchoring the screen to cathode potential and of avoiding parasitic oscillation must be enhanced by this inductance. Perhaps the authors could say whether cathode inductance has so far been found to have any appreciable deleterious effect.

Mr. E. B. Moullin: With regard to the telescoped Schottky effect mentioned in this paper, I am looking forward to the publication of the results of an investigation on this subject by Mr. G. W. Warren. It will be interesting to know how this subject has been affected by Mr. E. W. B. Gill's recent paper,* which seems to show conclusively that the Schottky effect does not follow the Schottky law, but varies as the inverse half-power of the voltage.

It is amazing to learn that the life of valves is now so predictable a quantity and that it is so closely related to the diameter of the filament.

Messrs. M. Ponte and **R. Warnecke** (France) (*communicated*): Our experience indicates that insulators which are subjected to high voltages at high frequency in the hot parts of thermionic valves do not give satisfactory results.

We think, like the authors, that the practice of fitting insulators between the grid and the anode is impracticable because of the excessive voltage which normally exists between these electrodes. We have found, however, that insulators between grid and anode can be adopted even with valves of the highest power without introducing any difficulty from the point of view of operation; it is in fact employed in nearly all the types of high-power valves used by the Société Française Radio-électrique. Valves constructed in this way are very robust and show great uniformity in their characteristics. The presence of a central guide makes the fitting of a filament-grid insulator relatively easy. It permits of a solid grid-filament construction which cannot be mechanically distorted in the transverse sense, yet allows expansion of the grid, central guide, and cathode.

* *Philosophical Magazine*, 1937, vol. 24, p. 1093.

The usual shape of valves enables insulators to be employed in situations where the temperature is low, without congestion and without increasing the size of the valve. For example, in a valve having a normal carrier output of 30 kW with Class B amplification the anode is only 530 mm. high and 113 mm. in diameter.

As regards grid seals in the form of a ring, we would draw the authors' attention to the difficulty of degassing these metal parts, which, it seems, must become heated in operation.

In reply to critics of the practice of fixing the grid by means of two arms sealed to the glass envelope, this system has a rather important advantage, especially for valves operating on short waves. By connecting the circuit formed by the grid and its two supports to a source of current it is possible to heat the metal of the grid sufficiently to degas it up to the level to which it is possible to heat the grid by electronic bombardment during the pumping process. This point is especially important in connection with short-wave valves, where large high-frequency grid currents are employed in normal operation. In valves rated at 150 A for normal use it is easily possible to pass a current of 1 500 A, i.e. to apply an overload such that the temperature-rise during the pumping process is much higher than that which exists in normal operation. This is a useful feature from the point of view of the final gas-absorption capacity of the sealed valve.

On page 178 the authors suggest that in valves having a low value of μ the grid may consist of rods parallel to the axis of the cathode. As no precise information is available as to the best value of μ to adopt for a valve operating as a Class B high-frequency amplifier, for example, it seems clear that when the authors refer to a valve with a low μ value they mean one which operates throughout the cycle with a negative grid voltage. This ought to be precisely stated, because it is impossible to imagine a valve with the grid made of rods parallel to the filament developing a positive grid-potential, due to the high grid-current of such a valve.

We do not agree with the authors that seals made of thick metal rods in glass may prove fragile. Our experience has shown, for example, that seals made of 10–20-mm. molybdenum rod in glass can be produced commercially without risk of breakage provided glass having the right properties is employed and a suitable sealing process is adopted. With regard to the use of seals on copper bezels, which we have employed for several years for filament-current connections, we find that direct seals made of rods have the advantage of fewer breakages and much greater ease of manufacture. By having a continuous conductor to carry the current one avoids troubles due to bad contacts or faulty bonding, both inside and outside the valve. This conclusion is supported by our experience as manufacturers and users of high-power transmitting valves. For copper-glass seals we have found it preferable to seal on both sides of the bezel with glass of a suitable coefficient of expansion.

We should like to know whether the authors have actually obtained all the expected advantage from anodes grooved on the outside from the point of view of the transfer of heat to the cooling water. We find that, for reasons not yet understood, increasing the surface area

of the anode in contact with the water gives no marked advantage. When in use on transmitters, however, grooved anodes are subject to the practical difficulty that they "fur" more rapidly than smooth anodes. The interior of the grooves becomes coated with talc which has the effect of reducing the cooling area as compared with a smooth anode.

The authors mention the possibility of blackening the interior of the anode in order to diminish the amount of heat reflected towards the envelope. A better way of achieving the same result is to employ channelling of suitable profile on the inside of the anode; this method seems preferable because the low stability of the deposit in the presence of heat sometimes limits the efficiency of degassing treatment, and also because the limited adhesiveness of the deposit may be the cause of flash-arcs.

The usual system of construction of valves does not always permit normal degassing of all the mechanical parts. Often the electrode supports and the current leads are only raised to moderate temperatures during the pumping process. Examination of data on the gas-emission of solids (particularly metals) seems to show that certain parts of the valve will give off gas constantly throughout its life because of the impossibility of raising them to a sufficiently high temperature during the degassing process. This gas tends to be re-absorbed by those parts of the valve which have been well degassed. The construction of the valve should therefore be such that the parts which cannot be heated during the pumping process are as few as possible. Our manufacturing experience shows that the degassing of very powerful valves is greatly helped if the heating of the anode is done by electronic bombardment instead of solely by radiation from the cathode; we think this to be due to the high activity (thermal or other) of high-speed electrons.

The application of a high voltage to the anode of a valve causes a fixation of the gas which reduces the pressure in the envelope; this fact may be confirmed by following the readings of a sensitive ionization gauge connected to the pumping tube of a large valve. These readings when plotted give a curve like that in the authors' Fig. 2. Was such an effect taken into consideration during the examination of their results?

The parallelism of the curves in Figs. 2 and 4, giving the backlash ratio and the photo-electric current, is striking; it was probably possible to investigate in these experiments the neighbouring points representing the K and L absorption limits of molybdenum. If the photo-electric effect is really due to the softest X-rays one ought to be able to find a curve which would give the law of variation of the continuous background emitted by copper with the accelerating voltage applied to the electrons, for the wavelengths in question. Have the authors made any investigations on these lines? Such investigations seem to us to be necessary because the authors rather under-estimate the importance of the primary emission from the grid, which most frequently sets the limit to the backlash current. This emission is due to the contamination of the grid by the particles detached from the anode under the influence of electronic bombardment. We may therefore consider that a state of equilibrium is reached at the surface of the grid which depends on the anode voltage and the grid temperature. The existence of backlash currents in the absence of an anode voltage, which vary according to the age and history of the valve, is evidence of this phenomenon.

We have examined the effect of the emission from the grid by methods enabling the grid to be heated by bombardment to normal working temperature and at the same time the backlash current of the valve to be measured in the absence of anode voltage. We find that the emission often begins at abnormally low temperatures and reaches high values under suitable working conditions. As, in certain instances, the phenomenon affects the value of the backlash current, even in the static condition which obtains during the process of measuring the space current, when the grid is only heated by radiation, we would ask the authors whether Curves A and B in Fig. 5 do not represent, partially at least, this heat-emission effect.

We have been able to verify, by different methods, the accuracy of the authors' hypotheses regarding the predetermination of valve characteristics. As regards the distribution of primary currents between the grid and the anode, the assumption that $I_g/(I_g + I_a)$ is a linear function of E_g/E_a is merely a first approximation which is very difficult to put to practical use. The terms which must be introduced into the second quantity in Lange's equation, namely

$$\frac{I_{g_1}}{I_{a_1}} = f\sqrt{\left(\frac{V_g}{V_a}\right)}$$

to take account of the space charge, do not reduce to a form justifying the linear relation mentioned above. We should like to know what the authors think of the use of the simple relation of Lange, by which it is possible either to calculate the distribution coefficient from the dimensions of the tube, making use of simple considerations derived from electron optics; or to measure the distribution coefficient at the points where $V_g = V_a$, the cathode being heated normally. We have found that for certain types of triodes, if corrections are made to eliminate errors due to the effect of the magnetic field and due to the secondary emission from the grid and the anode, Lange's law holds good as a first approximation when $V_g = V_a$ and the voltages are not too low; and it even holds for the case of an appreciable space-charge.

The reason why the greater part of the secondary emission from the grid comes from the ends of the grid is that, over the central portion, the primary space-charge retards the flow of electrons from the grid to the anode much more than that from the cathode to the anode. In this connection we would mention that merely by suitably choosing the position of the grid between the cathode and the anode it is possible to make the space charge between these electrodes act as a "stopper" grid. In valves of normal construction this phenomenon is related to the well-known effect produced by the magnitude of the total cathode emission on the distortion of the grid characteristic by secondary emission.

With regard to flash-arc breakdowns, some of our valves operate without troubles of this sort although their grid-anode distance is relatively small (20 mm.) and their working conditions are exacting (anode voltage

19 000–20 000 volts, with full excitation for a load which is constantly changing throughout the cycle of modulation). The fundamental factors which enter into the problem of flash-arcs seem to be the initial treatment of the electrodes and the nature of the impurities which may be deposited on their surface during the pumping process.

Messrs. J. Bell, J. W. Davies, and B. S. Gossling (*in reply*): In reply to Mr. Walker's points in connection with two C.A.T.14 valves at Droitwich, we feel that although they present similar phenomena the causes are different.

Valve No. 9a was in our opinion a straightforward case of softening, although at the time the cause was obscure. The possibility of a slow external leak proved, after extensive tests, to be out of the question. Grid emission was naturally a point which appeared to be an explanation for the high backlash, but after due consideration of actual facts there was no other alternative but to accept the high backlash as being due to high gas pressure.

When the valve was returned in the first instance, after some 1 000 hours' life, it was found that, out of some 700 μA reverse grid current, only 100 μA was due to grid emission. On the second occasion, after a further 1 000 hours' life, the grid-emission component of the total reverse grid current was even less, being only 25 μA in 1 000. From these facts there can be no doubt that the high backlash figures on this valve were due to softening.

During the history of cooled-anode valve development, we have, on various occasions, had reasons to believe that there do exist, in certain batches of metal, pockets or cavities which are not apparent on the surface. Such cavities would, under certain conditions, evolve gas at a slow rate and account for gradual softening. In more recent times we have some proof that such conditions are definitely possible. Cases have been examined where, on the inside surface of copper anodes, several blisters some few square centimetres in area and probably one half cubic centimetre in volume have appeared after heat treatment up to 500° C. In the early stages of gas escape from the pockets, the vacuum would be maintained by clean-up, but when the clean-up capability was exhausted the pressure in the valve would rise.

We do not think that the re-pumping of this valve was unnecessary. It was a clear case of softening, and, although at the time we were a little uncertain of the cause, more recent experience has proved that the action taken was justifiable.

The second valve No. 83 referred to is, we agree, a case of grid emission, but we would emphasize that such cases are extremely rare in our experience. The suggestion that the presence of thorium would account for the effect is reasonable but for the fact that in accepting the theory one is faced with another question, i.e. the origin of the thorium. In all high-power valves the filaments are pure tungsten and grids molybdenum or a combination of pure tungsten and molybdenum. That the grid emission is due to an active substance on the surface of the grid cannot be disputed, but we are sure that the active matter is not thorium. Sodium, potassium, or even copper oxide, can be considered as possible causes, but to which of these any definite case of grid emission can be ascribed is very difficult to say. Unfortunately, when grid emission cases have been examined no positive conclusions have been reached, probably owing to the evidence being destroyed when air is admitted into the valve.

Mr. Walker gives a figure of 1·15 amperes as the mean anode current of a C.A.T.6 valve in B.B.C. Regional transmitters. If the distortion factor is to be kept down to the low value of 4 % at 80 % modulation, the total emission of 10 amperes must be available throughout life. A longer valve life can only be obtained either by sacrificing quality or by using a lower mean anode current whilst retaining the same low distortion factor. The average life of 5 816 hours which Mr. Walker obtains from C.A.T.6 valves confirms the statement in the paper that, for an established type, the average life approaches the theoretical filament life—in this case slightly over 6 000 hours—and shows that the operating conditions must have been in every way satisfactory.

Mr. Moullin will be interested in this check of the predicted life carried out under accurately controlled conditions.

In reply to Mr. Grinstead on the subject of constant-emission operation, the important point really is that if a valve, operated throughout its life at constant filament voltage, is to have enough emission at the end of its life not to increase the distortion factor, then it must have much more than enough emission initially. The average life under these conditions will be depressed by very much more than the 15 % caused by constant emission operation. In other words, valve life is being wasted if there is excess emission at any time during life.

Mr. Grinstead also raises the question of differences in secondary emission between molybdenum and tungsten grids. It is our general experience that, in the secondary emission region, i.e. grid voltages below about 400 volts, greater secondary emission is obtained from molybdenum grids. This agrees with results of measurements of the secondary emission coefficient of molybdenum and tungsten.*

No relationship between X-ray photoelectric emission and secondary electron emission is known.

In reply to Mr. McLarty, we are quite confident that air-cooling, even of valves of the largest size, will be practicable.

With regard to the magnetic modulation of characteristics by alternating filament current, a distinction must be made between the effects as they exist in the valve, and the resultant " hum " which actually appears in the output circuit. For any given type of valve the hum level varies very widely according to the circuit conditions. Thus for the C.A.M.5 type, in which the modulation has been measured oscillographically, we understand that in the case quoted by Mr. McLarty the circuit conditions did not require the valve to amplify as well as to modulate.

In reply to Mr. Turner on the question of straight-line characteristics, the several controlling factors are not numerically investigated in every case. Nevertheless

* *L'Onde Électrique*, 1937, vol. 16, p. 516.

Fig. 10 is, as stated, representative of the great majority of types, including triodes, so that the three principles which he enumerates are now suitably included in the general tradition of valve design. Straightness of a large proportion of the characteristic is not, in general, necessary, though it is usually desirable that the upper part should be straight; the form of the lower part is also important. Thus, for instance, either for a single amplifier valve with a tuned load circuit of moderately high "Q," or for valves in push-pull with any type of load, a linear relation between input voltage and output current can be obtained from an individual dynamical characteristic which is parabolic in the lower part and passes upwards into a tangent line; in fact the characteristics of most valves approximate to this form. More generally, however, it can be shown that a linear response can be obtained from any characteristic which satisfies the condition that, the output current being expressed as a series of powers of the input voltage, this series shall contain no odd powers except the first. A parabola satisfies this condition, but since the apex is at the cut-off point, and the curve cannot rise again on the negative side of cut-off, the parabola has to pass upwards into a tangent line if the operating range is not to be unduly restricted. A hyperbola with an asymptote coinciding with the voltage axis also satisfies the condition. This shows that linearity is possible even with an extended "tail" at the foot of the characteristic.

With reference to Fig. 11 and its theoretical basis, what we have tried to do is to show that there are adequate theoretical reasons for supposing that all current values are, under the conditions outlined, multiplied by a common factor n, and all voltage values by another common factor $n^{\frac{2}{3}}$.

That the result of these multiplications is a diagonal displacement of a curve in Fig. 11 is surely a basic geometrical property of the log/log method of plotting. The only hiatus in the argument that we have been able to find is that we have omitted to state that the constant of the $\frac{3}{2}$ power relation between voltage and space-charge-controlled current for each element of the surface is independent of the temperature.

We hope that the matter will now be clear, for the principle is a very useful one; we may add, for instance, that the power-handling capacity of the valve is multiplied by $n^{\frac{5}{3}}$.

As to the heating current "leaving the positive end" of the filament, the electrons which constitute the current certainly do so, and we remain incorrigible in discarding convention and thinking of current in that way. If one does so it is at least always clear that the negative end must be the hotter.

We agree that we should have included a scale of dimensions in Fig. 6; actually, the external diameter of the anode is 8 inches.

The evaporated tungsten mainly comes down as a deposit on the anode, usually smooth but sometimes flaky, but in earlier days some of it used to appear as hairy or plate-shaped crystalline growths on the filament itself. In reply to Mr. Grinstead, for the check observations included in Fig. 7(b) it was not necessary to use the intermittent method, because with alternating-current filament heating a space-current of some 12 % of the heating current is not sufficient to affect the distribution of filament temperature.

In reply to Mr. Moullin about the Schottky effect, our difficulty in assessing the value of Mr. Gill's work is briefly as follows: Schottky's treatment starts from a very simple basis, the counteraction of the image force by the external field, and arrives at a relation involving a function of a certain exponential form including certain natural constants. Now exponential functions do not of their nature lend themselves very well to exact numerical verification—we all know what log plots are—but in this case the values of the constants have been verified with great exactitude, e.g. by de Bruyne in the work cited. This is our real stumbling-block, for Mr. Gill proposes to substitute an empirical function supported only by a very tentative theory which gives no clue to the values to be expected for his constants. We feel that cases such as oxide-coated or thoriated surfaces, in which Schottky's theory fails, and may be expected to fail since they violate his initial assumption of a smooth homogeneous surface, suggest that the Schottky theory should be suitably extended rather than discarded in favour of an alternative with an entirely different basis.

Mr. Turner asks for a definition of "equilibrium pressure." This descriptive term is used because the pressure as measured represents a balance between the liberation of gas from the electrodes, etc., and the disappearance of gas by clean-up.

The fixation of gas referred to by Messrs. Ponte and Warnecke is what we have called "clean-up." The effect is particularly noticeable in a valve having a large clean-up capability and a little free gas. When a high anode voltage is applied and a little anode current is allowed to flow, the free gas rapidly disappears and the backlash ratio approaches the photoelectric limit. This treatment was applied to the valve before the curve of Fig. 2 was taken.

During our work on the X-ray photoelectric effect no investigation was made into the K and L absorption limits of molybdenum, or into the variation of intensity of the soft X-rays with exciting voltage. Further information on these points can, however, be obtained from the original work of Richardson and Robertson.*

Regarding the magnitude of the photoelectric component of grid current: this, even for the largest valve, is but a few hundred microamperes and is small compared with the grid current which flows during normal operating conditions. Thermionic grid emission may be many orders of magnitude greater than the photoelectric component, but it was checked that Curves A and B of Fig. 5 were in no way influenced by thermionic emission from the grid. For the valves described in the paper the operating grid temperature is below that at which thermionic emission from the metal itself occurs, and it is only in extremely rare instances, such as that mentioned by Mr. Walker, when a contaminant of the sort described by Messrs. Ponte and Warnecke finds its way to the grid surface that thermionic emission from the grid is encountered.

The disadvantage of de-gassing anodes by bombard-

* *Proceedings of the Royal Society*, A, 1927, vol. 115, p. 280, and 1929, vol. 124, p. 188.

ment is that clean-up inevitably proceeds simultaneously and some of the gas evolved by the anode is cleaned-up in other parts of the valve. In some cases this may not be a serious disadvantage, but it is our experience that perfectly satisfactory valves can be produced without anode bombardment.

Before considering the further points raised by Messrs. Ponte and Warnecke we should like to mention their recent publication,* which is on similar lines to the present paper.

Regarding the relative merits of different forms of cathode seals, it is, to some extent, a matter of personal experience and technique whether the water-cooled rod type of seal or the cone type described in the paper is preferred. We do not agree, however, that bad contacts can be cited as a defect of the latter type of seal. In our experience this fault is entirely negligible.

No comparison with chrome-iron seals was intended in the paper. We have never used this type of seal and therefore have no experience of it.

Reference has been made to the circular grid seal as used for type C.A.T.17. This seal, of course, forms a very convenient mounting for the grid system, and as far as distribution of high-frequency current is concerned it is at least as good as two side seals of conventional type. A great advantage of the circular seal described is the large surface area available for contact. This is important when currents of the order of 100 amperes are being handled under normal operation, and, owing to the large dimensions of the seal, it is capable of dealing with current overloads due to mistuning, etc. The temperature-rise of these seals in operation is small, and the temperatures reached during normal evacuation are sufficient to ensure that no further gas is evolved under running conditions. We agree with Messrs. Ponte and Warnecke that it is often desirable to employ special methods of de-gassing the grid seals and leads of short-wave valves, particularly when the assembly is not so lavishly designed as that of type C.A.T.17.

In reply to Mr. Greig, constructions in which the high-frequency current is by-passed from the grid supports by flexible low-inductance strips have been considered, and in fact have recently been adopted experimentally. The effect of the inductance of the cathode leads in conventional valves usually becomes apparent before transit-time effects. Fortunately, however, the cathode may be brought to earth potential by means external to the valve, e.g. by the use of a half-wavelength line between cathode and earth. On this account it has not so far been found necessary to reduce the inductance of the internal filament leads.

We do not understand the remarks of Messrs. Ponte and Warnecke on the subject of low-μ grids. We have called a μ value of less than 10 "low" and such grids are usually made in the form of parallel rods. Valves of this sort, with μ as low as $6 \cdot 5$, are quite commonly in operation under Class B high-frequency conditions where the grid voltage becomes positive during part of the cycle.

Where we use grooved anodes to increase the effective area the jacket is brought in so close that there is no possibility of the water-flow avoiding the grooves, and we do not find that deposits form more rapidly in the grooves than on what remains of the outer surface of the anode.

We do not agree that channelling of the inside of the anode is better than blackening. On the contrary, although we use channelling in some cases its effect is less than we had hoped, and blackening has a much greater effect. Choice of a suitable material avoids the other difficulties mentioned.

Turning now to the division of current between anode and grid, we should first make clear, as we may not have done in the paper, that the observations on which diagrams such as Fig. 13 are based always include readings taken with anode and grid at the same potential. For most purposes, therefore, the "straight line" is used for interpolations within a not-very-large gap. Our principal concern has been with I_g as a correction to extrapolated values of I_a, rather than with estimation of the I_g characteristic itself or with the grid dissipation. We have thus not given the question so much study as Messrs. Ponte and Warnecke.*

However, we should like to put forward some comments in reply to their queries. In Lange's work the factor $\sqrt{(E_g/E_a)}$ appears at an early stage after comparison of the respective fields and space-charge distributions along lines between cathode and grid member and between cathode and grid space. The actual arguments by means of which he introduces it appear to us to be fallacious, though we would not deny that there may be some relation between the voltage-ratio and the space-charge. It has, however, been pointed out long ago by J. J. Thomson,† and more recently confirmed by Treloar,‡ that this same factor $\sqrt{(E_g/E_a)}$ must also appear when the deflection of the electrons by a charged grid wire is considered. This aspect is dealt with by Lange by means of his "correction angle" β, but is not made the subject of analytical treatment. It seems, therefore, that his simple formula, as quoted by Messrs. Ponte and Warnecke, needs to be extended so as to include both of the effects of the factor $\sqrt{(E_g/E_a)}$. The footnote to M. Warnecke's paper seems to imply that they are of the same opinion. Further, it seems that Lange's treatment of the space-charge of primary electrons in the neighbourhood of the grid wires, which is what we named the "incoming space-charge," only includes the effects of those electrons which actually strike the grid. Other electrons, however, which have been retarded by the local grid field but are deflected so as not quite to strike the wire, must also contribute to the local space-charge and increase its effect. It may be remarked here that in large valves the total surface area of the wires in the active parts of the grid is only about three times the cathode area, and the deflection of electrons by a negatively charged grid must effectively reduce to a small fraction of the total the main area bombarded. The current density in the bombarded areas is therefore quite high, and the combined effect of the bombarding electrons and their neighbours may therefore be considerable. It was for this reason that we were inclined to ascribe the suppression of secondary emission by local reversal of the field to this "incoming space-charge." We confess, however, that we have

* *Bulletin de la Société Française Radio-électrique*, 1938, vol. 12, p. 29.

* *Loc. cit.* (concluding footnote).
† *Journal I.E.E.*, 1920, vol. 58, p. 682.
‡ *Proceedings of the Physical Society*, 1936, vol. 48, p. 48.

omitted to consider the outward movement of the main cathode space-charge, as discussed by Lange, as a contributory factor. Finally, in all cases where it is known that the grid current is influenced by the magnetic field of the filament current to the extent that it is in large valves no purely electrostatic theory, such as the suggested extension of Lange's, can be regarded as providing a sound basis without careful consideration. This subject is difficult and complicated and we are much indebted to Messrs. Ponte and Warnecke for their observations.

We are indebted to Mr. Gibson and Mr. Pennington for their interesting contributions to the discussion. We find they have left us nothing to say in reply.

ANNUAL DINNER, 1938

The Annual Dinner of The Institution was held at Grosvenor House, Park Lane, London, on Thursday, 10th February, 1938, when the President, Sir George Lee, O.B.E., M.C., presided over a gathering numbering 1 111. Among those present were: The Rt. Hon. E. L. Burgin, LL.D., M.P. (*Minister of Transport*); The Rt. Hon. Lord Snell, C.B.E., LL.D., J.P. (*Chairman, London County Council*); The Rt. Hon. Lord Rayleigh, F.R.S. (*President, British Association for the Advancement of Science*); Sir Thomas Gardiner, K.C.B., K.B.E. (*Director-General, General Post Office*); Sir James Rae, K.C.B., K.B.E. (*Under-Secretary, Treasury*); Sir Henry Tizard, K.C.B., F.R.S. (*Rector, Imperial College of Science and Technology*); Sir Edward Crowe, K.C.M.G.; Sir William Bragg, O.M., K.B.E., F.R.S. (*Honorary Member, I.E.E.; President, Royal Society; Fullerian Professor of Chemistry, Royal Institution*); Sir Cyril Hurcomb, K.B.E., C.B. (*Chairman, Electricity Commission*); Sir John E. Thornycroft, K.B.E. (*President, Institution of Mechanical Engineers*); Sir Geoffrey Clarke, C.S.I., O.B.E. (*President, Association of British Chambers of Commerce*); Sir Maurice Simpson, C.S.I.; Col. Sir Thomas F. Purves, O.B.E. (*Past-President*); Sir Emsley Carr; Sir Montague Hughman; Sir Archibald Page (*Past-President I.E.E.; Chairman, Central Electricity Board*); Sir Robert H. Pickard, D.Sc., F.R.S. (*President, Institute of Chemistry*); Dr. E. F. Armstrong, F.R.S. (*Chairman, British Standards Institution*); Mr. W. J. Bache (*President, Incorporated Municipal Electrical Association*); Mr. G. J. Th. Bakker (*Member of Council, Koninklijk Instituut van Ingenieurs*); Prof. Henry Balfour, F.R.S. (*President, Royal Geographical Society*); Mr. A. Beverley Baxter, M.P.; Mr. A. Berkeley (*Chairman, British Electrical and Allied Industries Research Association*); Mr. A. C. Bostel (*Hon. Secretary, Sheffield Sub-Centre*); Mr. L. Browett, C.B., C.B.E. (*Permanent Secretary, Ministry of Transport*); Mr. D. M. Buist (*Past-Chairman, North-Eastern Centre*); Mr. E. S. Byng (*Member of Council*); Mr. W. A. S. Calder (*Chairman of Council, Society of Chemical Industry*); Mr. C. Augustus Carlow (*President, Institution of Mining Engineers*); Mr. L. H. A. Carr, M.Sc.Tech. (*Hon. Secretary, North-Western Centre*); Mr. E. Graham Clark (*Secretary, Institution of Civil Engineers*); Mr. J. G. Craven (*Chairman, North Midland Centre*); Mr. J. M. Donaldson, M.C. (*Past-President, I.E.E.; President, Incorporated Association of Electric Power Companies*); Mr. S. B. Donkin (*President, Institution of Civil Engineers*); Prof. F. G. Donnan, C.B.E., LL.D., D.Sc., F.R.S. (*President, Chemical Society*); Dr. S. F. Dorey (*Chief Engineer Surveyor, Lloyd's Register of Shipping*); Mr. J. F. Driver (*Hon. Secretary, East Midland Sub-Centre*); Mr. R. N. Eaton (*Hon. Secretary, Irish Centre*); Dr. W. H. Eccles, F.R.S. (*Past-President*); Lieut.-Col. K. Edgcumbe, T.D. (*Past-President*); Dr. S. English (*President, Illuminating Engineering Society*); Mr. J. L. Eve (*Chairman, Transmission Section*); Mr. C. E. Fairburn, M.A. (*Member of Council*); Mr. F. Lindsay Fisher, C.B.E. (*President, Institute of Chartered Accountants*); Dr. A. P. M. Fleming, C.B.E., M.Sc. (*Vice-President*); Prof. C. L. Fortescue, O.B.E., M.A. (*Member of Council*); Mr. P. Good (*Member of Council*); Mr. J. S. Highfield (*Past-President*); Mr. H. P. Hill (*Chairman, Association of Consulting Engineers*); Mr. T. St. Quintin Hill, C.M.G., O.B.E. (*Comptroller-General, Department of Overseas Trade*); Mr. A. G. Hiscock (*Hon. Secretary, Hampshire Sub-Centre*); Mr. Frank Hodges, J.P. (*Central Electricity Board*); Mr. H. Hooper (*Chairman, South Midland Centre*); Mr. W. D. Horsley (*Chairman, North-Eastern Centre*); Mr. P. V. Hunter, C.B.E. (*Past-President*); Mr. Alfred Hutchinson (*President, Iron and Steel Institute*); Mr. J. M. Kennedy, O.B.E. (*Past-President*); Mr. E. M. Lee (*Member of Council*); Mr. E. Leete (*Member of Council*); Mr. J. McCandless, M.Sc. (*Hon. Secretary, Northern Ireland Sub-Centre*); Mr. W. McClelland, C.B., O.B.E. (*Honorary Treasurer*); Mr. Charles Malegarie (*President, Société Française des Électriciens*); Prof. E. W. Marchant, D.Sc. (*Past-President*); Mr. S. W. Melsom (*Member of Council*); Mr. R. B. Mitchell (*Hon. Secretary, Scottish Centre*); Mr. F. E. J. Ockenden (*Member of Council*); Mr. W. Parry, M.Eng. [*Hon. Secretary, Mersey and North Wales (Liverpool) Centre*]; Dr. Clifford C. Paterson, O.B.E. (*Past-President, I.E.E.; President, Institute of Physics*); Mr. G. K. Paton [*Chairman, Mersey and North Wales (Liverpool) Centre*]; Major L. H. Peter, A.F.C., M.C. (*Chairman, Radio Manufacturers' Association*); Mr. G. L. Porter (*Past-Chairman, North-Western Centre*); Mr. H. B. Poynder (*Hon. Secretary, North-Eastern Centre*); Mr. R. H. Rawll (*Hon. Secretary, South Midland Centre*); Mr. E. A. Reynolds, M.A. (*Past-Chairman, South Midland Centre*); Dr. Russell J. Reynolds, C.B.E., M.R.C.P. (*President, British Institute of Radiology*); Mr. R. Richards [*Hon. Secretary, West Wales (Swansea) Sub-Centre*]; Prof. A. E. Richardson, A.R.A., F.R.I.B.A. (*Vice-President, Royal Institute of British Architects*); Mr. P. L. Rivière (*Member of Council*); Mr. C. Rodgers, O.B.E. (*Member of Council*); Dr. A. Russell, M.A., LL.D., F.R.S. (*Past-President*); Mr. H. Shaw (*Hon. Secretary, Tees-side Sub-Centre*); Mr. S. R. Siviour (*Past-Chairman, North Midland Centre*); Mr.

W. R. T. Skinner (*Hon. Secretary, North Midland Centre*); Brigadier H. Clementi Smith, D.S.O. (*Colonel Commandant, Royal Corps of Signals*); Mr. H. C. Smith (*President, Institution of Gas Engineers*); Mr. Roger T. Smith (*Past-President*); Mr. Thomas Smith, F.R.S. (*President, Physical Society*); Mr. J. W. Thomas, LL.B. (*Chairman, North-Western Centre*); Prof. W. M. Thornton, O.B.E., D.Sc., D.Eng. (*Past-President*); Prof. M. W. Travers, D.Sc., F.R.S. (*President, Faraday Society*); Mr. H. Cobden Turner (*Chairman, Meter and Instrument Section*); Mr. H. S. E. Vanderpant (*Mayor of Westminster*); Mr. T. Wadsworth, M.Sc. (*Chairman, Wireless Section*); Mr. H. E. Walker (*President, Electrical Contractors' Association*); Mr. C. R. Westlake (*Member of Council*); Mr. G. A. Whipple, M.A. (*Member of Council*); Mr. R. S. Wood (*Principal Assistant Secretary, Technological Branch, Board of Education*); Mr. W. B. Woodhouse (*Past-President*); Mr. Johnstone Wright (*Vice-President*); Mr. H. T. Young (*Past-President*); and Mr. P. F. Rowell (*Secretary*).

The toasts of "His Majesty the King," and "Her Majesty the Queen, Her Majesty Queen Mary, and the other members of the Royal Family," were proposed by the President and were loyally received.

The Rt. Hon. E. L. Burgin, LL.D., M.P. (*Minister of Transport*), in proposing the toast of "The Institution of Electrical Engineers," said: "Your Institution is one of the greatest engineering societies, and what a record it has! In the name of the Government I wish to pay a tribute to that great body of scientific opinion, always available, readily accessible, and placed at the disposal of the executive of the day.

"It would be invidious to refer to any particular respect in which your Institution has catered for modern needs. The growth of electricity is almost fantastic. As a mere consumer of coal, you have passed beyond the total consumption of the four main-line railways. I find that of the 230 million tons of coal raised a year, about 50 million tons are sent abroad and 175 million tons are used for some form of home consumption. Of that 175 million tons, 45 millions are consumed in the domestic grate, and of the remainder you rank high with your 15 million tons. Railways, as I have said, come in somewhere lower down.

"I thank your Institution, then, for all that it stands for; and, knowing something of the professional bodies which grant diplomas and degrees, I salute the integrity of your ruling body whose standards are not challenged and who keep high the level of technical efficiency which you require before a member can use the initials A.M.I.E.E. after his name.

"One of the major responsibilities cast upon my shoulders as the titular head of your industry is to endeavour to frame a measure to provide for the distribution of electricity throughout these islands in a way which will be a practical and technical advance on the conditions existing at the time of the McGowan Report. To that anxious task I am bringing such talents as I possess, with the earnest desire that, with the help of as skilled a body of technicians as can be found, culled from the Electricity Commissioners and my own Ministry, we may make a measure alike workable and acceptable and in the interests of the consuming public, who must be our main thought throughout any reorganization of this kind. You will hardly expect a more detailed announcement in advance of my placing my proposals before the House of Commons.

"I am allowed to couple this toast with the name of your President, Sir George Lee. We consider the Post Office service to be one of the greatest assets of which our country may well be proud, and we know how much your President was responsible for the international radio transmitter at Rugby. Rugby is the greatest world transmitter, and perhaps wireless broadcasting is one of the greatest potential instruments for peace that mankind has ever discovered—and heaven knows how much mankind is in need of potential instruments for international peace at this hour!

"I give you the toast of your Institution, coupled with the name of your President."

The President, in responding to the toast, said: "I should like to convey, on your behalf, our most sincere thanks to the Minister of Transport for coming here to-night and proposing this toast. As he has mentioned, he is the titular head of the electrical industry in this country; but apart from that there are very urgent and weighty matters upon which we should have liked to hear him speak. We agree, however, that it is necessary for Parliament to hear those proposals before we do.

"The history of our Institution has been admirably described in a brochure published by The Institution, but I should like to give you a less-hackneyed account, my theme being based upon the idea that scientific methods and scientific thought take a long time to develop. I propose to go right back to the times of the Saxon and Norman noblemen, when they used to appoint an official whose duty it was to taste the wines and food, so that no poison should be introduced into the food intended for his Lord and Master. Later on, the liverymen of the City of London appointed officials to test the goodness of ale and it is related that Shakespeare's father held such an appointment at Stratford-on-Avon. The method of tasting, or testing, as it came to be called, was to pour some ale on to the seat of a Windsor chair. The testing officer, clad in buckskin breeches, seated himself on the chair, and if the breeches stuck to the chair it was regarded as positive proof that sugar had been added to the ale. This may be regarded as the beginning of scientific method in our medieval history. Then we had the Royal Society formed in 1660, the Royal Institution in 1800, and later the Institutions of Civil Engineers and Mechanical Engineers, and finally in 1871 The Institution of Electrical Engineers, which was then known as the Society of Telegraph Engineers. This is, very briefly, the development from ale-testing to the wizardry of electrical science. We still combine these operations—the Chairman of our General Purposes Committee has the duty of testing the wine list at this dinner, and it may reassure the members to know that his absence to-night is not due to an 'accident on duty,' but to his presence at an International Conference at Cairo.

"I have recently come across in the Post Office records some unpublished items concerning our history. The first is in the year 1880, when the Society of Telegraph

Engineers petitioned for a charter of incorporation. This petition was submitted to the Postmaster-General of the time for his advice, and, rather curiously, he did not seem to be at all interested in the matter and, as there was some opposition elsewhere, the petition was declined. As you know, we did not succeed in obtaining our charter of incorporation until 1921.

"The other item was in 1883, when the Society of Telegraph Engineers was holding a conversazione at South Kensington to which foreign delegates to an International Telegraph Conference which was being held in London at the time were to be invited. Application was made to the Postmaster-General for some telegraph apparatus which it was desired to exhibit at the conversazione. The Postmaster-General agreed to lend the apparatus, but, with that care for the national finances which has always distinguished successive Postmasters-General, he stipulated that the cost of conveyance, if any, of the apparatus from the Post Office to South Kensington should be borne by the Society. I have ascertained that the Post Office engineers of those days possessed a horse and cart and as no additional cost was incurred the Society did not, in fact, burden its funds with this charge.

"Most of us in the room know what electricity has done and is doing, but we do not know what it is going to do in the future. We know that it has provided our homes and offices with clean, soft, radiant light. We know that it is going to light our main roads sooner or later, and it will be unnecessary to keep the lighting on all night, because road contacts could switch the lamps on and off. As a motorist I hesitate to let the Minister of Transport know that the electrical engineer could provide the road authorities with means for measuring the speed of a motor-car with great accuracy and quite automatically, and it would even be possible to take photographs of the registration numbers of offending cars.

"We know that electricity runs our railways, our trams, and our trolley-buses; we know that there are many applications of electric power in factories, mines, and offices, whilst heating and other aids to comfort and health are provided. We know that electricity has produced many aids to navigation in the form of direction-finding, wireless, and depth sounding, and many developments are taking place in these fields. I am quite sure that the aids to navigation, both for marine transport and for aviation—in allowing, for example, blind landing—will be very much developed in the near future.

"Agriculture and horticulture are becoming electrically-minded, and we have developments such as soil-heating which will doubtless improve horticulture in particular. The medical profession also has developed electrical appliances very thoroughly; and in the way of electrotherapy, radiology, surgical instruments, etc., many active developments are taking place which will have very beneficial results for humanity. Finally, we have our leisure looked after by broadcasting and television.

"All these advances in electrical development are due to research. Research in the electrical industry is a very highly organized branch which advances in knowledge step by step on the foundations of previous knowledge. The Institution, in addition to initiating and stimulating research, is in effect a vast educational body which promulgates these steps of knowledge by the scientific papers and discussions at its proceedings. I think, therefore, that we may take some pride—in that modest way which is characteristic of engineers—in having had the opportunity to play our part in the development of what we may truly call the Electrical Age.

"Finally, I should like again to express our thanks to Dr. Burgin for coming here to-night, and to say to him that we hope that his guidance of the new Bill in Parliament will keep the green light showing for the electrical industry not only this year but for all time."

Dr. A. P. M. Fleming, C.B.E., M.Sc. (*Vice-President*) then proposed the toast of "Our Guests," to which **Mr. A. Beverley Baxter, M.P.,** responded.

A reunion was subsequently held.

A METHOD OF USING HORIZONTALLY POLARIZED WAVES FOR THE CALIBRATION OF SHORT-WAVE FIELD-STRENGTH MEASURING SETS BY RADIATION*

By J. S. McPETRIE, B.Sc., Ph.D., Associate Member, and B. G. PRESSEY, B.Sc.

[From the National Physical Laboratory.]

(*Paper first received 17th November, 1937, and in final form 22nd February, 1938.*)

SUMMARY

The paper describes a method for the calibration of short-wave field-strength measuring sets by radiation using a loop transmitter in the horizontal plane. It is shown experimentally that in the case of vertically polarized waves† the simple ray theory does not apply unless the transmitter and receiver are both elevated to considerable heights above the ground. With horizontally polarized radiation, however, the simple ray theory holds on short waves for practically all heights of transmitter and receiver. This distinction between the propagation characteristics of the two types of radiation suggests the use of horizontally polarized waves for field-strength calibrations on short waves. The advantages ensuing from the use of horizontally polarized waves for this purpose may be summarized as follows:—

(*a*) The heights of transmitter and receiver may be reduced practically to any extent, so that high masts are no longer required.

(*b*) For low heights of transmitter and receiver the reflection coefficient of the ground is sensibly unity for all types of the earth's surface, so that little error can be introduced in the analysis due to wrong assumptions as to the electrical properties of the ground.

The analysis of the results is considerably simplified when the reflection coefficient of the ground is approximately unity.

(*d*) With no masts at the transmitter or receiver it is an easy matter to take an attenuation run, so that the calibration is not dependent on one observation.

(*e*) It is particularly suitable for the calibration of receivers incorporating rectilinear antennae, as there is no error in calibration due to varying height of the aerial above ground.

(1) INTRODUCTION

The enormous increase in the congestion of the radio channels on long and medium wave-bands has forced the radio engineer to investigate the possible uses for communication of the ultra-short waves less than 10 metres in wavelength. In order to determine the commercial possibilities of such waves a knowledge of their propagation characteristics is essential and this, in turn, entails a method of measuring field strength. The measurement of field strength at any frequency depends ultimately on the measurement of voltage or of the current through a known impedance. Even when voltage and current can be measured at high frequencies, numerous difficulties are encountered in practice, owing, amongst other things, to the disturbance introduced by the measuring instrument itself. Until an accurate and convenient method of measuring current is available for short waves, recourse must be had to the thermo-junction, the calibration of which with low-frequency alternating current is assumed to hold at the highest frequencies. It has been shown† recently that, with existing types of thermo-junction, the probable error introduced in this way in the 5- to 10-metre region is not more than 5 %. This error is sufficiently small for present-day purposes on this wave-band.

A small vertical loop transmitter has been used by American investigators‡ to produce by radiation an electromagnetic field in the neighbourhood of the receiver to be calibrated. By measuring the current in the transmitting loop of known area the field at the receiver can be calculated, allowing for the effect of the reflection at the ground. This ingenious method has the great advantage over the methods usually employed on longer wavelengths when applied to the ultra-short wave-band that no extraneous leads or impedances of doubtful magnitude are added to the receiver during calibration. In order to minimize the effect of the ground, and so the error due to possible wrong assumptions as to its reflecting properties, the transmitter and receiver are usually placed approximately one wavelength above the ground and about half a wavelength apart. This entails the use of relatively high masts, and the calibration is dependent on one disposition of transmitter and receiver. With the radiation method described below, using horizontally polarized waves, the receiver calibration can be made for low heights of transmitter and receiver. The subsequent analysis of the results is considerably simplified, and by measuring the attenuation of field strength with distance the calibration can be made dependent on a series of observations. It is shown in the paper that the calibration obtained in this way is the same as that with vertically polarized radiation between transmitter and receiver, each of which is at a height above the ground comparable with the wavelength.

(2) DESCRIPTION OF TRANSMITTER

A loop transmitter was used because of the uniform radiation in all directions in the plane of the loop, when the perimeter of the latter is small compared with the wavelength. The current in the loop which constituted

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

† Throughout this paper, the expressions "vertically" and "horizontally" polarized waves are used to mean radiation of which the electric vector lies in and perpendicular to the plane of incidence, respectively.

† See Reference (1).

‡ *Ibid.*, (2).

the inductance of the oscillatory circuit of the transmitter as well as the radiating source was measured by a non-contact type of thermo-junction the couple of which was connected by a twisted pair of No. 40 gauge copper wires to a microammeter of small dimensions. The radiation

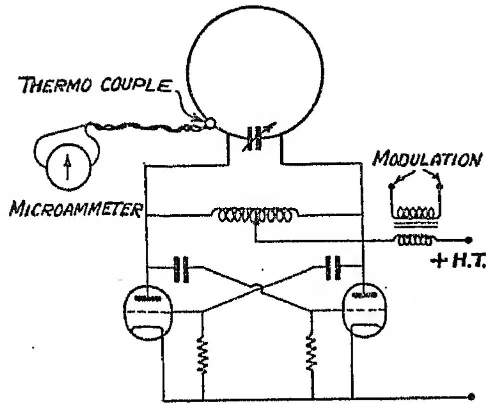


Fig. 1.—Circuit diagram of transmitter.

from such a transmitter is similar to that of a magnetic doublet at the centre of the loop. If the loop is placed near any reflecting surface, such as a metal box containing the radio components or battery supply of the oscillator, an image of the primary radiating source is formed in the box. The effect of this image is to alter the radiation distribution of the transmitter to an indeterminate extent. For this reason all screening of the oscillator was dispensed with and the radiation due to high-frequency currents in parts of the oscillator other than the loop was reduced to a minimum by making the physical size of all components of the oscillator, except the loop,

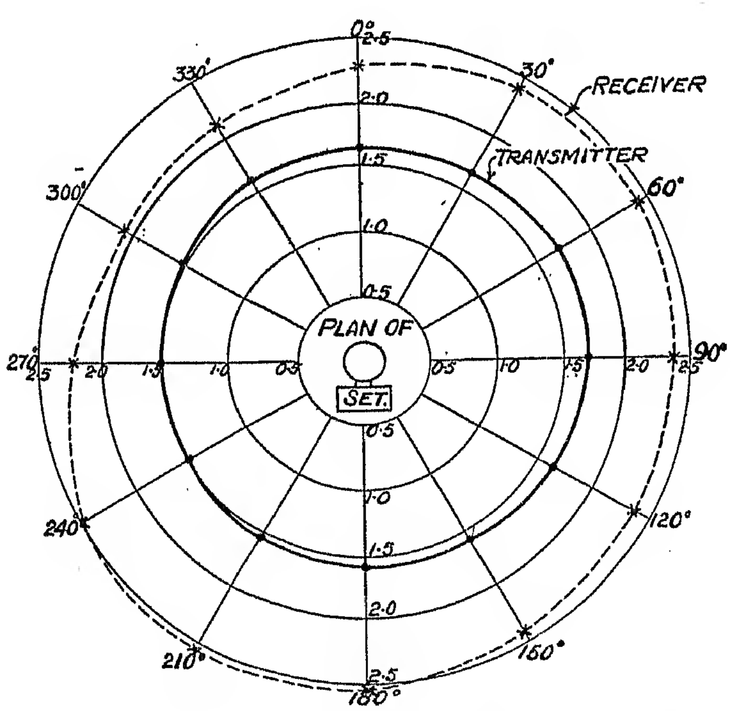


Fig. 2.—Polar diagrams of transmitter and receiver.

as small as possible. In order to maintain electrical symmetry in the loop so that the "antenna effect" of the loop and the high-frequency current in the high-tension lead should both be small, the push-pull circuit as shown in Fig. 1 was used, incorporating two acorn valves. The battery leads were arranged perpendicular to the plane of the loop, and the batteries (of an unspillable type) were lashed to a platform parallel to the plane of the loop and distant from it by about 4 ft. By this disposition of the components of the transmitter the polarization of the radiation from high-frequency currents in the battery leads was in a plane perpendicular to that of the loop and could not, therefore, induce any e.m.f. in the receiver loop when the latter was orientated so as to receive the radiation from the transmitter loop.

The usual law for the radiation from a loop source assumes that the current throughout the loop is uniform. The degree to which this condition holds in any particular case can be determined by finding the magnitude of the departure from uniform radiation in all directions in the plane of the loop. On account of the reflection occurring at the earth's surface the most convenient way to make this test is to place the radiating loop horizontally and to measure the horizontal field at a fixed receiver for different orientations of the transmitting loop. This test was made on all wavelengths for which the transmitter described above was used as a standard radiating source. For a given loop perimeter it was found, as would be expected, that the variation with direction of the received signal from its mean value increased with decrease in wavelength, but with the loop sizes used the total variation was always less than 10 % of the mean field. It can be assumed, therefore, that the calculation of field from the usual formulae involving the loop dimensions and current, hold to at least the same accuracy. The full-line curve in Fig. 2 shows the polar radiation distribution found in this way for a loop perimeter of 0·96 m. on a wavelength of 8 m. (35·5 Mc./sec.).

(3) DESCRIPTION OF RECEIVER

The receiver was of the superheterodyne type incorporating a single-turn loop as the aerial and also as the inductance of the first circuit. A block diagram of the receiver is given in Fig. 3 so that the disposition and dimensions of its components may be appreciated. The small metal box directly under the aerial loop contains the frequency-change unit consisting of two diodes in push-pull, with appropriate beat oscillator diodes being used so that overloading in this stage of the receiver was prevented. The amplitude of the local oscillator voltage was sufficient to ensure that the intermediate frequency output was independent of this voltage. The output from the frequency-change stage is transferred by means of a screened lead to the intermediate-frequency amplifier contained in the large metal box. The wooden box at the bottom of the receiver contains all the batteries. Before making a measurement of field strength the gain of the intermediate-frequency amplifier was adjusted by varying the grid-bias of the valves, so that with the frequency-change unit disconnected the thermal-agitation noise in the first intermediate-frequency circuit produced a standard reading of the output meter. The frequency-change unit was then connected to the amplifier, tuned to the frequency of the radiation on which a measurement was required, and resistance attenuators in the intermediate frequency amplifier were adjusted so that the reading of the output meter was the same as that given by first-circuit noise and no attenuation. By the initial adjustment of the intermediate-frequency amplifier, the overall amplification of the receiver could always be set to the same value, since the use of diodes in the

frequency-change unit allowed of no alteration in the response of that part of the receiver.

A loop aerial was used in the receiver because in the experiments to be described two waves from the transmitter were incident at the receiver, one by the direct path and the other after reflection at the ground. For elevated transmitter and receiver these two waves were not in the same azimuth, so computation could be reduced considerably by using at the receiver a loop aerial having uniform "pick-up factor" for all directions in its own plane. In order to test whether the large metal boxes of the receiver affected the circular polar diagram of the receiving loop, the receiver was placed with its loop in the horizontal plane and all its components arranged with respect to each other and the plane of polarization of the incident radiation in exactly the same manner as for the reception of vertically polarized waves. The height of the receiving loop above the ground was 1·2 m. and the receiver was so arranged that it could be tuned by means of strings by an operator at a distance of about 2 m.

The horizontal field at the receiver was measured as the transmitter with its loop arranged horizontally at a

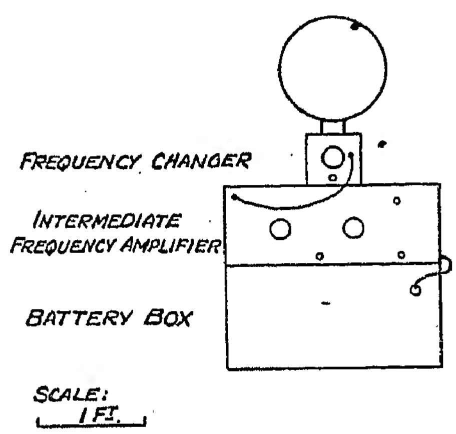


Fig. 3.—Scale diagram of receiver.

height of 0·84 m. was moved to a series of positions 30° apart at a constant distance of 25 metres from the receiving loop. In order that the polar radiation distribution of the transmitter should not affect the results, the transmitter loop remained in a fixed direction at each position relative to the radial line to the receiver. The observations were repeated with the receiver rotated through 180° about the vertical axis through its loop. By taking the average of the two measurements (the maximum difference was about 10 %) for the same position of the transmitter relative to the receiver loop, the effect of any spurious reflections from nearby conductors was reduced. The results of measurements made at a wavelength of 8 m. are shown by the dotted curve in Fig. 2, from which it is seen that the maximum variation of received signal from its mean value is ± 7·5 %. This variation was sufficiently small for the radiation reception distribution of the receiving loop to be considered uniform.

(4) SIMPLE RAY THEORY OF WAVE PROPAGATION

The radiation in the immediate neighbourhood of a transmitting aerial is extremely complicated. At distances from the source greater than about one wavelength, however, the radiation may be considered as that of a plane wave. The earth behaves in many ways as a radiating source when radiation is incident on its surface. For this reason the plane-wave theory may not apply if the radiation is required from a transmitter placed near the earth at a receiver also at a low height. Let T, Fig. 4, represent a source of strength I at such a height h_1 above the ground that the radiation incident on the earth may be considered as plane, and R that of a receiver also at an appreciable height h_2. The radiation incident at R can be considered as that due to the primary source I at T and a secondary source at the image point of T in the earth. The strength of this secondary source is $\rho f(\theta) I$, in which ρ is the reflection coefficient of the ground for plane waves of the appropriate frequency and angle of incidence θ, and $f(\theta)$ represents the polar radiation distribution of the source at T. The magnitude of the reflection coefficient and the phase change on reflection for any condition of reflecting surface and angle of incidence can be determined from a series of curves given by one of the authors.* If the source at T is a vertical single-turn loop the value of $f(\theta)$ is unity and the field at the receiver is then given by

$$E = \frac{120\pi^2 AI}{\lambda^2}\left[\frac{1}{a} + \frac{\rho}{b} e^{\frac{2\pi j}{\lambda}(b-a)}\right] \qquad (1)$$

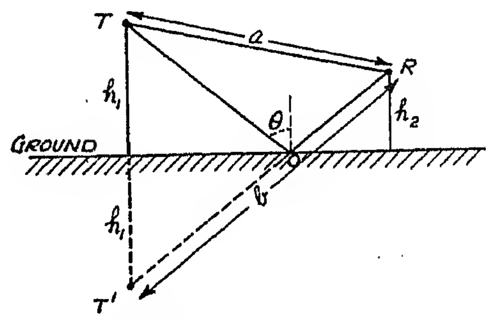


Fig. 4.—Diagram showing (a) direct and (b) reflected wave equivalent paths between elevated transmitter (T) and receiver (R).

in which A is the area of the radiating loop, I the current in the loop in amperes, λ the wavelength, and a and b the distances TR and T′R. The field is given in volts per unit of the dimension of length used in equation (1). When the product $h_1 h_2$ is very small compared with the horizontal distance D between transmitter and receiver

$$\rho \rightarrow -1$$

$$\frac{1}{a} \simeq \frac{1}{b} \simeq \frac{1}{D}$$

and

$$(b - a) \simeq \frac{2h_1 h_2}{D}$$

Equation (1) then reduces to

$$E = \frac{480\pi^3 AIh_1 h_2}{\lambda^3 D^2} \qquad (2)$$

Equation (2) should give the attenuation of vertically polarized waves along the ground if the conditions for plane-wave propagation apply. It can be shown that equation (2) is equally true for horizontally polarized waves under the same conditions.

* See Reference (3).

(5) EXPERIMENTAL PROCEDURE AND RESULTS

(a) Vertically Polarized Waves

The propagation of vertically polarized waves has been the subject of extensive study since the classical work of Zenneck* and Sommerfeld.† While much experimental work has been carried out previously on the attenuation of waves along the ground for longer wavelengths, it was considered desirable, for the purpose of this paper, to show experimentally that the attenuation of vertically polarized ultra-short waves at low angles of elevation along the ground is not given by equation (2), from which the field from a given transmitter should vary inversely as the square of the distance between transmitter and receiver, provided the product of transmitter and receiver heights is small compared with that distance. In order to test whether this condition applied to the propagation of vertically polarized waves, the receiver described in Section (3) was set up with its loop in the vertical plane and at a height of 1·65 m. above the receiver. Measurements made with a distance of 60 m. between transmitter and receiver showed, however, that no change of field strength occurred when the height of the transmitter was increased from 1·5 to 2·25 m., while the receiver height remained fixed at 1·65 m.

The results obtained show, therefore, that equation (2) cannot be used to determine the field at low elevations for vertically polarized waves. It was pointed out above that if the transmitter and receiver are both elevated to considerable heights from the ground the re-radiation from the earth is plane at the receiver and the laws given by the ray theory are correct. In order to calibrate the receiver with vertically polarized waves, the receiver was located at the top of a 20-ft. wooden-lattice tower. The transmitter was raised to a height of 40 ft. on a light wooden mast which could be easily moved from one position to another. The transmitter loop was supported on a 3-ft. pole projecting horizontally from the

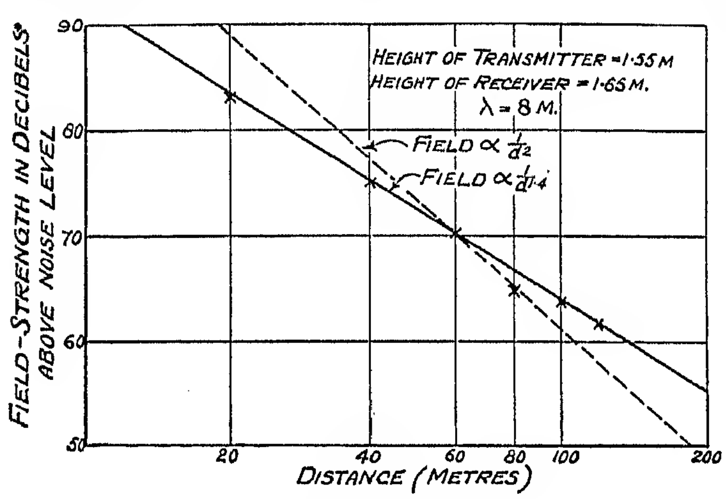


Fig. 5.—Variation of field strength with distance for vertically polarized waves.

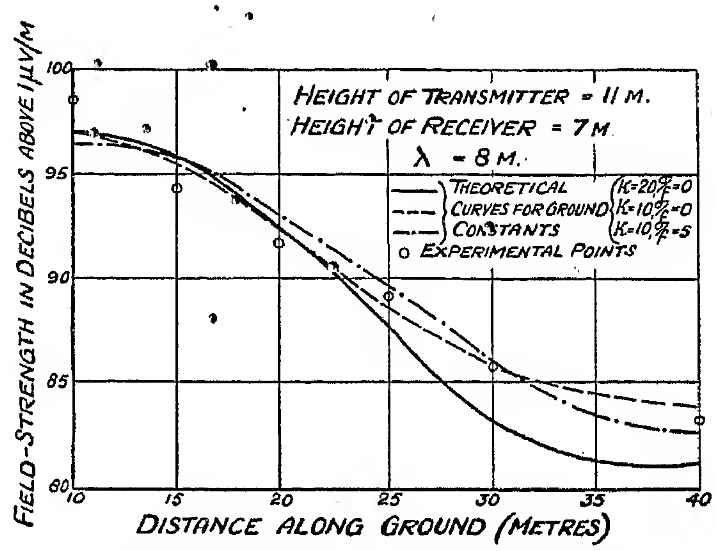


Fig. 6.—Variation of field strength with distance for elevated transmitter and receiver for vertically polarized waves.

ground. The transmitter (Section 2) with its loop in the same vertical plane as that of the receiver loop, and at a height of 1·55 m., was placed in turn at various distances between 20 and 120 m. from the receiver. The field strength at the receiver in relative values was determined for a constant current in the transmitting loop operating on a wavelength of 8 m. (37·5 Mc./sec.). The field strength measured in this way is shown on logarithmic scale in Fig. 5 plotted against the corresponding distance. The dotted line in the same figure is the inverse-square law given by equation (2). The departure from the experimental values of field strength given by this relation is greater than that which can be accounted for by experimental error. The full line, which is the best mean through the experimental points, satisfies the relation‡

$$\text{Field} = \text{constant}/(\text{distance})^{1\cdot 4} \quad . \quad . \quad . \quad (3)$$

According to equation (2) the field strength should be proportional to the height of either transmitter or top of the mast in a direction perpendicular to the plane of propagation. Relative measurements of the field at the receiver were made for horizontal distances between transmitter and receiver of from 10 to 40 m.

The calculation of the field strength at the receiver necessitated the use of equation (1), as the heights of the transmitter and receiver were no longer small compared with the distance between them. The only way in which the magnitude of the reflection coefficient in this expression could be determined was to assume values for the dielectric constant κ and the conductivity σ of the earth's surface at the frequency f of the radiation used, determine the value of ρ from Fresnel's equations for the angles of incidence corresponding to each position of transmitter, and find which values of these constants gave the curve in Fig. 6 nearest in shape to that obtained experimentally. The values of earth constants at 8 m. considered as limiting values and taken to determine ρ were $\kappa = 20$, $\sigma/f = 0$; $\kappa = 10$, $\sigma/f = 5$; and $\kappa = 10$, $\sigma/f = 0$.

The calibration of the receiver required was to determine the field which would give the standard output with no signal attenuation. Assuming this field to be 1·8 μV/m., the experimental results obtained are shown by the circles in Fig. 6. It will be seen that they lie closely to the theoretical curves for $\kappa = 10$ and $\sigma/f = 0$ or 5.

* See Reference (4). † *Ibid.*, (5).

‡ This relation is approximately the same as that found by Burrows for short-distance propagation over water. He states that this variation of received field strength agrees with that derived from the formulae given by Weyl and Norton (C. R. BURROWS: "The Surface Wave in Radio Propagation over Plane Earth," *Proceedings of the Institution of Radio Engineers*, 1937, vol. 25, p. 219). The electric field for vertically polarized waves is not given accurately in magnitude by equation (2), but over the range of distances used in these tests the variation should, according to the ray theory, be approximately inversely proportional to (distance)².

Therefore, the magnitude of a field which produces the standard output with n decibels attenuation in the receiver is n decibels above $1 \cdot 8\ \mu V/m$.

(b) Horizontally Polarized Waves

The departure of the law of radiation observed with vertically polarized waves at large angles of incidence from that given by equation (2) is to a large extent due to the rapid variation with angle of incidence in the reflection coefficient of the ground for such waves. The full and dotted curves in Fig. 7 give the reflection coefficients for ground constants $\kappa = 10$, $\sigma/f = 0$, for vertically and horizontally polarized waves respectively, for angles of incidence between 86° and 90°. It will be seen that the rate of change of reflection coefficient with angle of incidence is much less for horizontal than for vertical polarization. This result suggests that equation (2) might apply for horizontally polarized radiation for relatively small heights of transmitter and receiver. In order to test this the receiver was set up with its loop horizontal as in the experiments described in Section (3).

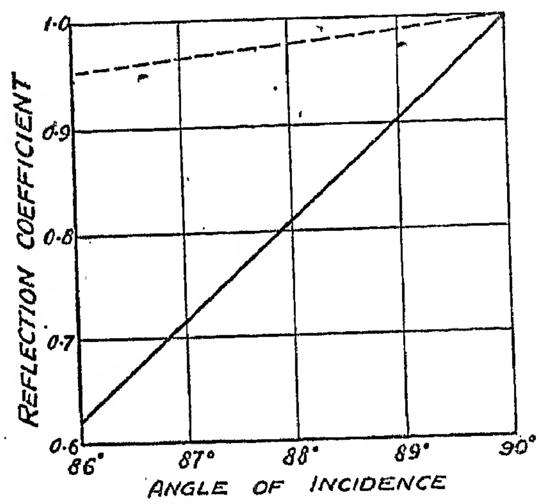


Fig. 7.—Reflector coefficient/Angle of incidence for ground constants $\kappa = 10$, $\sigma = 0$.
- - - - - - Horizontal polarization.
——— Vertical polarization.

The transmitter with its loop also horizontal was placed with respect to the receiver so that its radiation was incident on the receiving loop in the same azimuth as vertically polarized radiation from a distant source when the receiver was used for the reception of such waves. The heights of transmitter and receiver were respectively 1·20 and 1·15 m. The field strength at the receiver was measured relative to noise-level with the transmitter at various distances between 20 and 140 m. The experimental results obtained on a wavelength of 8 m. are plotted in Fig. 8 as field strength in decibels above noise-level in the receiver against the distance on a logarithmic scale. The points lie within experimental error on the full line in the same figure, which is given by equation (2), viz.

$$\text{Field strength} \propto \frac{1}{(\text{distance})^2}$$

Equation (2) also shows that if the ray theory can be applied at low angles of elevation the received field should be proportional to transmitter height, other factors remaining constant. The transmitter and receiver with loops horizontal were placed 100 m. apart, and while the receiver height remained fixed at 0·8 m. the transmitter height was varied in steps from 0·6 to 2·7 m.

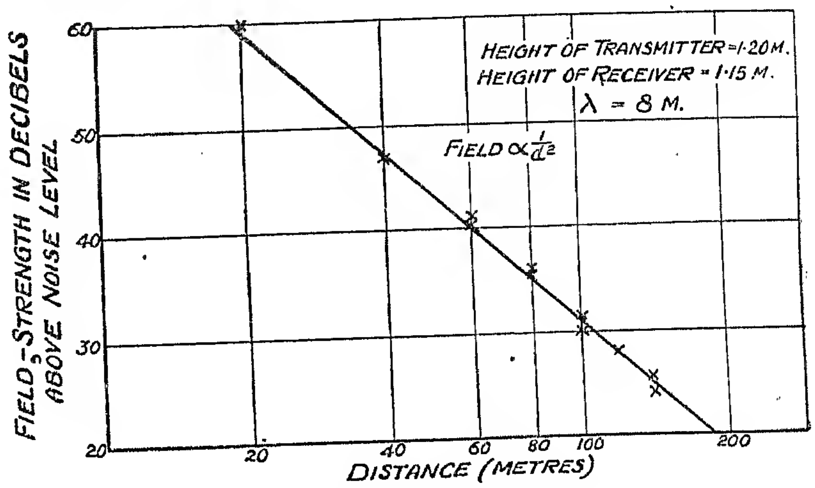


Fig. 8.—Variation of field strength with distance for horizontally polarized waves.

For each height of transmitter the field strength at the receiver was measured for a constant current in the transmitting loop. The field strength in decibels above noise-level is plotted in Fig. 9 against the logarithm of transmitter height. The full line is given by the relation

$$(\text{Field strength}) \propto (\text{Transmitter height})$$

The experimental points lie closely to this line, so that the field strength at the receiver is proportional to transmitter height for horizontally polarized waves. It follows from the theorem of reciprocity that a similar result would have been obtained if the height of the receiver instead of the transmitter had been changed. This means that the field strength at a low receiver from a low horizontal transmitter is proportional to the product of transmitter and receiver heights.

The measurements with horizontally polarized waves show, therefore, that the propagation of such waves is in agreement with equation (2), which was arrived at on

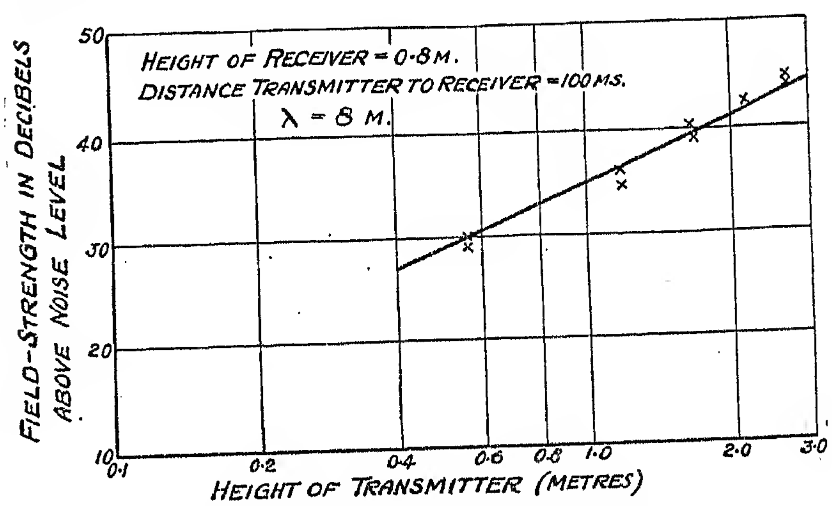


Fig. 9.—Variation of field strength with height of transmitter for horizontally polarized waves.

the assumption of plane-wave propagation. The logical deduction from this result is that, to the accuracy obtainable with the receiver used for the measurements, the conditions of plane-wave propagation can be assumed with horizontally polarized waves for all practical heights

of transmitter and receiver. The field at a distance of 100 m. for the transmitting conditions obtaining in the experiment calculated according to equation (2) is $64 \cdot 3\ \mu V/m$. The corresponding reading of the field strength measured at the receiver in decibels above noise-level is $31 \cdot 5$. Hence with the horizontal method of calibration by radiation the field strength corresponding to zero receiver attenuation for the standard output is $31 \cdot 5$ db. below $64 \cdot 3\ \mu V/m.$, that is $1 \cdot 7\ \mu V/m.$*

(6) COMPARISON OF THE TWO METHODS OF RECEIVER CALIBRATION

The closeness with which the experimental results given in Fig. 6 can be made to agree with the calculated values of field strength shows that under the conditions specified the assumption of plane-wave reflection at the ground was justified. The calibration using elevated transmitter and receiver should, therefore, be correct within experimental error. The field strength equivalent to the standard output determined in this way was $1 \cdot 8\ \mu V/m$.

With the method using horizontally polarized waves, the results given in Figs. 6 and 7 show that the relation between field strength and transmitter and receiver heights and distance is that obtained in equation (2). The magnitude of the field under given conditions need not, however, be given by this equation. The calibration of the field strength for standard output, assuming equation (2) to be correct, was $1 \cdot 7\ \mu V/m.$, which agrees within experimental error with the value $1 \cdot 8\ \mu V/m.$ obtained with vertically polarized waves. The horizontal method of calibration with small transmitter and receiver heights and the supposition of plane-wave reflection may be used, therefore, for the calibration of short-wave receivers.

(7) CONCLUSIONS

The investigation described above leads to the following conclusions.

(*a*) The simple ray theory does not apply to the propagation of vertically polarized waves directly along the ground.

(*b*) In order that the simple ray theory may be applied for short distances the transmitter and receiver must be raised off the ground to heights comparable with the wavelength.

(*c*) The computation of the field under the conditions specified in (*b*) is laborious, and the accuracy of the result is dependent on correct assumptions as to the electrical properties of the ground.

(*d*) The simple ray theory applies to the propagation of horizontally polarized waves of wavelengths less than 10 m. for all practical heights of transmitter and receiver.

(*e*) Result (*d*) suggests the use of horizontally polarized waves for the calibration of short-wave receivers by radiation. Low transmitter and receiver heights can then be used. The computation of the field at the receiver under this condition is very easy and accurate, as at grazing incidence the reflection coefficient is practically unity for all types of ground.

(*f*) The calibrations of a receiver using vertically and horizontally polarized radiation for high and low transmitter and receiver heights, respectively, agreed within 10 %.

(8) ACKNOWLEDGMENTS

The work described in this paper was carried out as part of the programme of the Radio Research Board, and acknowledgment is due to the Department of Scientific and Industrial Research for granting permission for publication. The authors are also indebted to Mr. F. M. Colebrook for the design and construction of the receiver used in the investigation, to Dr. R. L. Smith-Rose for advice on the method of presentation of the paper, and to Mr. B. J. Byrne for assistance in the experimental work.

* Equation (2) was deduced on the assumption that the reflection coefficient of the ground was exactly -1. A more complete expression for the field, taking into account the departure of the value of the reflection coefficient from unity, is

$$E = \frac{120\pi^2 AI}{\lambda^2 d}\sqrt{\left[\left(\frac{4\pi h_1 h_2}{\lambda d}\right)^2 + \frac{4(h_1+h_2)^2}{(\kappa-1)-2j\frac{\sigma}{f}}\right]}$$

in which κ and σ are the dielectric constant and conductivity of the ground at the frequency f, the other symbols having the same meaning as in equation (2). This more exact expression for the field suggests that for the conditions in the present experiments the calibrations using equation (2) is approximately 20 % too small. The results of the experiment with varying height of transmitter at a fixed distance, however, suggest that the required correction was smaller than this. The exact amount, if any, of this correction was impossible to determine with the receiver used in the tests.

REFERENCES

(1) J. H. MILLER: "Thermocouple Ammeters for Ultra-High Frequencies," *Proceedings of the Institute of Radio Engineers*, 1937, vol. 24, p. 1567.

(2) J. C. SCHELLING, C. R. BURROWS, and E. B. FERRELL: "Ultra-Short Wave Propagation," *ibid.*, 1933, vol. 21, p. 427.

(3) J. S. McPETRIE: "The Reflection Coefficient of the Earth's Surface for Radio Waves," *Journal I.E.E.*, 1937, vol. 82, p. 214.

(4) J. ZENNECK: "Propagation of Plane Electromagnetic Waves along a Plane Conducting Surface, and its Bearing on the Theory of Transmission in Wireless Telegraphy," *Annalen der Physik*, 1907, vol. 23, p. 846.

(5) A. SOMMERFELD: "Propagation of Waves in Wireless Telegraphy," *ibid.*, 1909, vol. 28, p. 665.

DISCUSSION ON

"MODERN SYSTEMS OF MULTI-CHANNEL TELEPHONY ON CABLES"*

NORTH MIDLAND CENTRE, AT LEEDS, 9TH NOVEMBER, 1937

Mr. R. M. Longman: I am struck by the design of the outer conductor of the coaxial cable, which consists of an interlocking copper ring—the idea presumably being to keep this truly circular. A somewhat similar design of interlocking conductor is being employed both for oil-filled cables and for aerial conductors. In this case the sections of the conductor dovetail into each other. It would be interesting to know the total cost of the London–Birmingham cables with all the repeater stations and other equipment *en route*.

I should be interested to know whether still better arrangements than those in use at present can be made for the transmission of indications on the 'grid' system between the various substations and the control room.

Prof. L. S. Palmer: We all realize the great demand there will be for television as soon as distribution by cable becomes practicable, and it is interesting to speculate on whether the cables described in the paper will be capable of meeting the television demands of only a few years hence. It is my opinion that telegraph and telephone engineers will be forced to use higher and higher frequencies in order to accommodate the ever-increasing number of relatively wide bands which these services will require. So far, an increase in frequency has resulted in an increase of energy-loss accompanied by corresponding technical difficulties, some of which follow from Fig. 18. There is reason to suppose that at very high frequencies these losses will not go on increasing at the rate indicated by the extrapolation of this Figure. I should like to inquire, firstly, whether work at ultra-high frequencies has yet been undertaken and, if so, whether the difficulties (in particular those due to dielectric losses) did, in fact, increase as might be anticipated from Fig. 18; and secondly, whether there is any way of meeting the future demand for many wide channels other than that of continually increasing the frequency of the currents.

On page 595 reference is made to thermostatically-controlled crystals. I should like to inquire why critically-cut crystals are not employed. They would at least be more economical.

Finally, there is the question of the phase distortion which a signal will suffer when travelling along a cable at a group-velocity less than that of light *in vacuo*. This is likely to be a very serious distortion when television pictures have to be transmitted by cable over long distances. I should be interested to know what attempts have been made to minimize or counteract this particular form of distortion.

Mr. F. G. C. Baldwin: Not long ago we were content to employ one or two independent metallic conductors as a medium for the transmission of telephone speech; in fact, no other means was available. There followed attempts to increase the number of channels for communication by super-imposition—" phantom " and then " ghost " circuits—but these had decided limitations and disadvantages. Now, as we learn from the paper, those limitations have been removed, and the use of conductors of new and special design employing carrier currents of high frequency marks a new era in telephone transmission.

In Fig. 17 the authors give a cross-section of the London–Birmingham coaxial cable; I should be glad if they would explain the purpose of the brass tapes and the thin lead sheath surrounding them. Such a sheath can hardly be for mechanical protection, nor is it, I imagine, likely to prevail against penetration of water if the outer sheath is perforated. Am I correct in my recollection that in one coaxial cable the lead was absent and a steel tape was included?

We have been accustomed to deal with breakdowns on paper-core cables of all descriptions and lengths, and have developed an organization for attending to such mishaps with reasonable promptitude. One of the most important considerations is to localize and arrive at the fault before water, which is almost invariably present in quantity, has penetrated so far that the cable cannot be repaired *in situ*. In the old types of cable, a certain resistance to the rapid penetration of moisture along the length of the cable was encountered by reason of the relative congestion of the insulated pairs, a perhaps fortunate feature which is absent in the coaxial cable. I should be glad if the authors could tell us something about the effect of water gaining access first to the outer core and secondly to the coaxial cores. If the core sheath of the coaxial cable is perforated as well as the outer sheath, as is very likely in cases of mechanical damage, there seems to be nothing to impede the progress of water within the tube at an alarming rate. Is it practicable to withdraw the water, and, if so, in what way?

Has the desirability of maintaining the coaxial cable under air pressure been considered? This has been done with dry-core cables, in which any loss of air pressure denotes a leak demanding remedial measures. The practice has not, however, been considered to be worth while for general use.

Whilst it is relatively easy to provide and arrange for automatic switching of stand-by amplifiers and their associated equipment, a stand-by coaxial cable would be impracticable on the score of expense. It is therefore imperative that, as far as is economical and practicable, such a cable should be safeguarded from breakdown.

The ultimate developments of multi-channel working in telephone cables are not yet in sight, and perhaps the authors might be disposed to undertake the somewhat risky venture of prophecy in regard to the possibility of

* Paper by Col. A. S. Angwin and Mr. R. A. Mack (see vol. 81, p. 573).

multi-channel working in subscribers' cables. Our local cable systems with their multiplicity of conductors may ultimately give place to abbreviated cable systems adapted to multi-channel working, somewhat on the lines described in the paper.

Mr. William F. Smith: The authors state that, in order to minimize the effects of possible reflections, the cable (in the case of the 12-channel system) is graded between repeater stations so that inequalities in capacitance are gradual. Presumably the selection of lengths has to be done before the cable is drawn into the ducts, and after the drawing-in process it is possible that the characteristics of the cable will be slightly different. Since, in any case, the variations in characteristics will be small, it is doubtful whether any advantage is gained by matching. Is there any evidence of the efficacy of grading of the cable?

In the case under review it is indicated that very little increased cross-talk arises when end-of-section balancing is resorted to instead of mid-section balancing. This is a rather astonishing result, considering the small variations in capacitance that are concerned; these can produce considerable cross-talk at the high frequencies used. If it can be assumed that all cases will produce similar results, a large economy in accommodation costs is likely to accrue from employing end-of-section balancing. In addition, the amount of leading-in and jointing of cables will be reduced by this type of balancing.

I should be interested to know the function of the compensating network on the input to the common transmitting amplifier in Fig. 4.

As is mentioned in the paper, considerable accuracy is necessary in the design of the filters when dealing with very high frequencies, and stray capacitances become of vital importance. One would therefore think that great care would be necessary in screening the components, but apparently no serious attempt is made at efficient screening or earthing of the apparatus used, more particularly on the wide-band system.

Atmospheric changes would appear to have an important bearing on the correct functioning of the equipment, and possibly hermetic sealing of most of the components would be an advantage. The flatness over a wide band of frequencies of the gain curve of the feed-back repeater shown in Fig. 7 suggests a theoretical rather than a practical result. Was this curve actually obtained in practice?

Turning to the coaxial wide-band system, I venture to touch on the question of economics. We are providing here a means of transmitting about 400 channels on two pairs of cables. A cable of, say, 400 pairs of the ordinary type could be laid in the same or probably a smaller duct space than the coaxial cable. The total costs of the new and old systems would probably be of the same order, and, apart from the possible utilization of the coaxial cable for television programme transmission, there does not appear to be any gain from the traffic-capacity aspect. The proportion of the costs of the coaxial system invested in equipment (i.e. plant above ground) is probably very much higher than in the case of audio cables, and this should prove advantageous from the maintenance aspect.

Another practical aspect is that of the jointing of the section lengths, which will be, as far as one can see, a very complicated procedure and will demand considerable experience on the part of jointers.

It is stated by the authors that the variation due to change of temperature on the coaxial cable between London and Birmingham is of the order of 30 db. at a frequency of 2·1 Mc./sec. over a period of 12 months, but I understand that experience on the New York–Philadelphia cable showed a figure of 0·8 db. per mile at 1 Mc./sec. This would represent, on the London–Birmingham system, 100 db. at 1 Mc./sec., and considerably more at higher frequencies. The control of the variation due to temperature is at present performed manually, but there seems no reason why it should not be controlled automatically from the output of the amplifiers. Such an arrangement would provide a smoother control over the quality of transmission.

Mr. R. J. Hines: Telephony emerged from the sphere of the science laboratory into that of practical engineering with the development of methods of switching. The facility for putting telephones in communication with each other rapidly was essential before telephony could develop as a public utility. The next impetus came from operating personnel, who sought more and more facilities and conveniences for the handling of the increasing telephone traffic. To-day the fundamental problems of transmission have been solved. The greatest separating distance is no impediment to perfect speech transmission, and within the limits of commercial telephony—I am not speaking of music transmission or television—the transmission expert is not now faced with problems of increased range or improved quality, but with the problem of an increase in the capacity of one physical circuit for carrying speech channels. Increased utilization of cable pairs may be a great attraction to the transmission engineer, but from the point of view of public service rapid and accurate establishment of the desired connection is even more important.

The development of high-frequency transmission is involving the switching engineer in a reconsideration of the whole of his technique. In the past he has been able to attack his problems with the knowledge that for any one connection he had one complete physical circuit entirely at his disposal. The number of signals and facilities he could offer was equal to the number of permutations of the conditions he could apply to a pair of wires: for instance, he could have potential connected to one wire and earth to the other at either or both ends; he could during the course of the call reverse that potential, and with the introduction of metal rectifiers he could determine the polarity of the potential. All these means of discrimination were brought into play in such circuits as those in which a single junction circuit is used for calls to either the auto-manual board, or the automatic plant at an auto-manual exchange, the discrimination being effected by the electrical conditions applied to the physical circuit. Now, however, the switching engineer has no physical circuit to use, but merely a band of frequencies utilized for the transmission of speech. He has succeeded in differentiating between speech frequencies which represent speech and speech frequencies which do not represent speech. It must be recognized, however, that the conditions within which

he is being asked to work are very exacting. He could only make the distinction referred to above by utilizing as signals a combination of frequencies which, while they *may* occur in speech, are yet unlikely to do so. Though the 2-voice-frequency signalling system has proved practicable it is dependent upon a principle which the circuit designer has always sought to avoid, namely a marginal or selective operation instead of the utilization of a unique condition to represent a unique signal.

Multi-frequency systems offer a solution to this problem. The switching engineer would again be given scope to develop facilities if there were allotted to him his own band of freqencies; for instance, the coaxial system utilizes a range from 0·5 to 2·1 Mc./sec., commencing at the lower limit of 0·5 Mc./sec., solely because of the necessity of compressing the range of frequencies transmitted through one valve to a ratio of 1 : 4. Is there any reason why frequencies lower than 0·5 Mc./sec. should not also be transmitted and, by means of band-pass filters, be tapped off and amplified through a separate repeater, thus providing a further series of channels? A separate series of channels such as I suggest, working on a lower frequency band, will not suffer so great an attenuation as that to which the higher frequencies are subjected. Now if this lower range of frequencies were used for providing signalling channels, each one of which would be associated with its appropriate speech channel, a much narrower band than 4 kc. per channel could be used, thus providing as many signal channels as there are speech channels and yet of such a width that the signalling engineer would have as many individual frequencies as he desired within each channel. The fact that individual frequencies, and not a band, are required for signalling renders irrelevant the fact that one is working on the steep part of the attenuation/frequency curve. Moreover, if these frequencies were used for signalling channels, cross-talk would not be such an important factor as it is in the transmission of speech; for, while cross-talk must not be permitted to rise to such a level that false signals would result, nevertheless noises which would be intolerable on a speech circuit would be well below the level necessary to actuate switching gear.

With regard to the 2-voice-frequency signalling system, I feel that it is a matter of paramount importance that improved circuit occupancy shall not be gained at the slightest expense of accuracy of dialling.

Under "Conclusions," reference is made to the flexibility of the 12-channel system where small blocks of circuits are required. At a rapid glance it is not possible to visualize what equipment would be involved in segregating a small group of circuits from a coaxial system, but it does not seem theoretically impossible to detach as a spur a very small group, or even one circuit, by separating out the frequencies and re-combining those which are to be passed on. The matter would seem to be one wholly of economics in that demodulating equipment at a point where otherwise only a through repeater would be required, would obviously be somewhat expensive. While no doubt it it is impracticable to quote actual costs, the authors might be able to indicate the relative costs of a single channel on the coaxial and 12-channel systems.

The possibility of providing for television transmission is stated to have been a factor in the decision to proceed with the Birmingham coaxial cable. As these transmissions will require a frequency range up to the full 2·1 Mc./sec. for which the cable is designed, it seems that it can only be used if alternative provision is made for as many channels as are already in use for telephone traffic. I see that two of the four tubes in this cable are intended for television, but until provincial television transmissions become a regular feature the television cores will no doubt be used to meet urgent demands from the ever-expanding trunk service. The fact that there are four tubes in the cable leads me to inquire whether the next development will be the superposition of yet another multi-channel system as a phantom, two pairs of tubes being used as legs.

Mr. C. O. Horn: The authors refer to a desired diameter ratio of 3·6, but they do not state whether they have actually achieved this ratio in the coaxial cable. From Fig. 17 it is only possible to work out that the ratio is something less than 3·68.

The Birmingham–London coaxial cable runs through one of the worst parts of the country from the point of view of electrolysis, and I am therefore anxious to know whether any special anti-electrolytic methods have been used. I should also like to know whether any special anti-creeping devices have been introduced.

A repeater spacing of 6 to 7·9 miles is quoted in the paper. Is 1·9 miles tolerance the maximum that can be permitted? This margin strikes me as likely to be insufficient in a difficult case. When an amplifier-station site was being sought on the Birmingham–Oxford "voice plus single-channel carrier system" the tolerance limits permitted search to be made throughout the whole length of the cable as it passed through Stratford-on-Avon. The one possible site was about 10 yards inside the tolerance limits; it was only found after 3 months' hard search work.

Lastly, the authors quoted the percentage dielectric losses on the Birmingham–London cable and mentioned that these would be reduced on the Birmingham–Manchester section, and still further reduced on the Manchester–Newcastle section. I should be glad to know how those reductions are to be brought about, and particularly whether any radical change is contemplated in the design of the cable.

Mr. A. K. Robinson: I recently had the opportunity of studying the Bristol 12-channel system in some detail, and I was surprised to notice the use of coplanar-grid valves involving grid-bias batteries. This seems to be a reversion to old practice: is it likely to be rectified? The coplanar-grid valve itself is an innovation, and I should like to know whether there is any published information on it.

It is an unfortunate necessity of carrier working that one deals with very low input values, of the order of microwatts. In this connection I must comment on the increased demands made on the maintenance staff: they are now called upon to deal with currents which they cannot even measure. These increased demands must in the long run have a very considerable effect on the type of personnel required.

In spite of the low output values, the total consumption

of one of the 12-channel repeater stations mentioned in the paper is about 1 000 units a month as a minimum.

The fact that the currents in the coaxial cable are restricted by the skin effect to a very small thickness of the conductors raises two interesting points. One is the possibility of using duplex materials of the Sheffield-plate type, one to give the necessary electrical qualities and the other the mechanical qualities: has any consideration been given to that type of construction? The second point is the possibility of the characteristics of the cables being changed by ageing. The effect of oxidization might be to form a high-resistance semi-conducting surface, and it would be interesting to know whether any such effect has been anticipated.

The coaxial cable affords an interesting comparison of the American outlook with our own. We house equipment of the nature of repeaters in brick buildings of substantial construction, on which we spend much money. The Americans, on the other hand, appear to be quite content to put their repeaters in manholes, a course which we should probably never consider. Are their manholes better than our own, or are they more concerned with economy than with convenience?

Reference has been made by the authors to the possibility of using types of cable other than the coaxial for television signals (presumably referring to the screened-pair type). It has been stated elsewhere, however, that the coaxial cable is the only means of transmitting television signals over long distances. I should like to ask whether that is strictly correct, and whether there is any fundamental reason why the television signals should not be split into bands, transmitted over the 12-channel system, and reassembled at the far end. I admit there are practical difficulties, but the essential point is: What is the effect of an irregularity in the frequency response of the transmission system upon the television signal? The answer is, probably a flicker effect or a shadow pattern. The simplest method of trying this out would be to insert filters in some part of an existing television system. I should like to know whether anything has been done towards investigating this.

My final point refers to future possibilities. It is theoretically possible with the coaxial system to quadruple the frequency range by halving the repeater spacing, and I should like to know whether it is likely to be an economic and practical proposition to put in more repeaters at intermediate points should a demand for further channels arise.

[The authors' reply to this discussion will be published later.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 29TH NOVEMBER, 1937

Mr. J. Greig: It is rather remarkable that such an apparently simple device as the negative-feedback amplifier should be capable of minimizing the non-linearity of an amplifier to such an extent as to render possible the simultaneous amplification of upwards of 300 telephone conversations. It would be interesting to know whether the initial adjustment of the negative-feedback amplifier is much more difficult than that of the normal amplifier, and what criteria are used to determine when correct adjustment has been attained.

The negative-feedback amplifier would probably be of great value in the field of precise measurement, e.g. in the measurement or oscillographic observation of very small alternating voltages and in the determination of distortion or harmonic content in small voltages and currents. Where harmonic contents of the order of only 1–2 % are involved, the distortions introduced by an amplifier of normal design are themselves of the same order of magnitude as the quantity which it is desired to observe: the estimation of flux distortion in iron testing is a case in point.

In regard to the coaxial cable, it would be interesting to know something about the effects of phase-displacements. I assume that the equalizing networks ordinarily used in telephone work take account of magnitudes only, and are not concerned with phase-changes in the various frequencies transmitted. With television transmission, where the phase-changes inevitably introduced will be significant, some form of phase correction must presumably be employed; information on how far phase correction is necessary and how it is accomplished would, I think, be of general interest.

Mr. H. Faulkner: The paper describes the application of a technique which has been developed during the past decade for radio circuits, to the problem of the provision of land-line circuits. The application has necessitated the solution of many new problems, the production of new apparatus such as the negative-feedback repeater, and the compression of the apparatus to reasonable dimensions in view of the large number of circuits involved. Considerable advances have also had to be made in the technique of filter design, and in the production and methods of mounting of the necessary crystals both for filters and for constant-frequency oscillators. The method of obtaining the necessary constant-frequency oscillations from a single source is very intriguing, and may possibly have repercussions on the radio technique from which it is derived. It seems possible that in the future all frequencies used for radio transmissions may be allocated to national blocks, all controlled from a single master-oscillator.

It is not clear why all the valves in the negative feedback repeater described in the paper are of the "power" variety. It seems that considerable savings in power requirements, and consequent reductions in the voltage-drop along the cable in the case of power feeds to the subsidiary repeater stations, might be made possible by a re-design of this equipment. In view of the advantages claimed for the new form of modulator unit, I should like to ask the authors why a reversion has been made to the Carson modulator in some cases.

Mr. E. Lerpiniere: Is it possible yet to give details of the methods of signalling to be used over the coaxial cable with its wide range of speech bands?

Mr. J. A. Cooper: Will the authors state why the voltages of 130 V and 21 V mentioned on page 579 (vol. 81) were chosen in the first instance? Voltages such as these are not normally associated with small valves.

It would be interesting to have an explanation of the operation of the modulation circuit shown in Fig. 5. How does the resistance R referred to on page 580 enable "a useful working carrier voltage to be produced"?

On page 581 the amplifier illustrated in Fig. 6 is referred to as "well-designed." Fig. 6 gives no values of the components used, and I should therefore be glad to know what are the important points in the design.

On page 583 a psophometer is referred to; will the authors explain the principle of this instrument?

Mr. W. Ware: Is a very high insulation resistance required on coaxial cable, and would the intrusion of moisture affect the capacitance of the central conductor in such a manner as to upset the whole scheme of transmission?

Mr. G. Pinney: I should be glad if the author would say what is the probability of a complete breakdown of a coaxial cable. Such an event would be extremely inconvenient from a telephone traffic point of view, as it would mean the loss of 200 to 300 circuits simultaneously.

Mr. H. G. S. Peck: One of the problems which had to be solved in connection with the coaxial cable was the distribution of 320–400 bands of speech frequencies over the wide band which is transmitted over the cable. The solution adopted, that of using a frequency of 400 cycles per sec. applied from London (or Birmingham) to control 3 multi-vibrators at each end of the cable, producing the 21 carrier frequencies required, is extremely ingenious.

With regard to the transmission of power to the amplifier stations on the route, will this affect the variation of the temperature of the cable throughout the seasons, and therefore its transmission efficiency? I imagine that it is possible to determine what will be the temperature variation of the cable where it is not used for the transmission of power, but the difficulty is that some sections of the cable will be carrying power and others not, and they will therefore be at different temperatures.

Mr. J. Morton: Do the Post Office find it necessary to provide special drums in order to transport coaxial cable by road instead of by rail? It is not unknown for power cable wound on drums to be damaged by shunting operations on the railway, and I should like to know whether similar trouble is being experienced in connection with the far more delicately-constructed coaxial cable.

Mr. N. L. Hibbs: With reference to Mr. Pinney's remark as to the seriousness of coaxial-cable breakdowns, I should like to ask whether the precision testing methods and apparatus used for ordinary telephone cable will be applicable to coaxial cable, and whether any progress has been made towards the development of a system of automatic localization of faults by alarms, rather on the lines of the American pressure-gauge system.

Mr. A. W. Binns: There is one curious point in the circuit diagram of the feed-back repeater (Fig. 6) which I should like the authors to explain. The output valve seems to have two grids, which are shown as interlaced; I should like to know whether this symbol denotes a new type of valve, and, if so, what type.

Mr. H. Cooper: I should be glad to know what method has been adopted to prevent cable creepage with coaxial cable, or whether the existing method as applied to paper-insulated cables is thought sufficient. What is the purpose of the small pinhole in the centre of the ferrule surrounding the conductor joint? I should be glad to have some information regarding the dessication of coaxial cables, and as to whether local pressure-testing will be required as each joint is completed. Would it be possible to use silica gel in the joints?

Mr. C. J. Cameron: There are one or two fundamental differences in the principles used for the 12-channel and coaxial systems, and I should be glad if the authors would explain the reasons for these. In the first place, pre-equalization is used with the coaxial system to reduce the power handled by the amplifiers. It would seem that this feature is also of importance in connection with the 12-channel system, as the results shown in Table 2 for the short Exeter–Bristol section do not seem to be very satisfactory. Secondly, what, if any, are the objections to locking the carrier frequencies on the 12-channel system, on similar lines to the coaxial-system application?

On page 577 the electrostatic cross-talk current is given as ωKZ. Is the electrostatic coupling K in this formula the normal capacitance between P and Q?

Mr. G. R. Turtle: The authors mention that, on the 12-channel system, balancing networks are placed half-way between the repeater stations, and I should like to know why such networks are used. Presumably a reasonably good capacitance balance exists on cables in normal practice, and there is no need to add special balancing arrangements.

Is there any necessity to transmit electric power along the coaxial cable, seeing that electric light is provided at the intermediate repeater stations, and also electric power for soldering-irons and heaters if necessary?

The authors' first slides referred to the 1 + 1 and 1 + 4 channels; presumably these are 4-wire circuits using two pairs, one for "go" and one for return, and they are not used on the *Zweiband* system lately adopted on the Anglo-Dutch cable, where the audio-frequency "go's" and a return at carrier frequency are carried on the same pair.

Mr. R. H. Rawll: I should be interested to learn whether special methods are employed to exclude moisture from coaxial cable, and to maintain the necessary high degree of insulation between the central and outer conductors. Although these are displaced from one another by cotton string, a very considerable air space exists in each tube.

[The authors' reply to this discussion will be published later.]

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 6TH DECEMBER, 1937

Mr. Alfred Morris: Carrier operation is remarkable in two essential features: first, in that the intelligence is not transmitted in its original condition, but in a manner whereby its component frequencies are changed before

its passage along the transmitting medium. For example, in the 12-channel scheme the frequency of the ordinary speech band changes by as much as 60 kc., whilst in the coaxial system changes up to 2 Mc. are employed. The second respect in which carrier working is remarkable is in regard to the means whereby it permits of additional channels of communication being made available. Under the old method, additional channels necessitated the provision of additional lines, frequently involving extensive underground work. Nowadays, however, additional channels may be provided by increasing the amount of equipment at terminal stations. This feature is at the moment confined to the provision of trunk circuits, and a good many of us wish that we could deal in the same manner with the present exceptional demands for local lines. The fact that, with carrier working, additional channels of communication can be provided at relatively short notice, as compared with the old method whereby some considerable time elapsed before such channels were made available, has a large economic value which will need to be properly assessed.

Dealing specifically with the two systems described in the paper, the 12-channel system is a balanced system in which near-end cross-talk between oppositely transmitting pairs has been eliminated by the use of separate cables, whilst distant-end cross-talk between unidirectional transmitting pairs has been reduced, at least for frequencies up to 60 kc./sec., by special cable design, manufacture, and field balancing, as well as by the use of balancing networks. On the other hand, the coaxial system is an unbalanced system. The skin effect at frequencies above 0·5 Mc./sec. is such as essentially to confine working currents to the inner surface of the tube and interfering currents to its outer surface, with a consequent freedom from disturbance. The two tubes are used not because of any cross-talk feature but essentially from the point of view of "4-wire working." The practicability of both schemes is greatly dependent upon the use of the Black feed-back amplifier, whereby stability and freedom from harmonics has been obtained, as well as a very high gain for repeaters spaced at relatively close intervals.

What is the electrostatic capacitance per mile of a pair of the Bristol–Plymouth cable, and how does it compare with that of a long-distance multiple-twin cable? On the Edinburgh–Aberdeen cable, is the capacitance of the pairs the same as or greater than that of the pairs of the Bristol–Plymouth cable? I ask this question because advantage has been taken on the Edinburgh–Aberdeen of the star-quad form of cable, with its superior space feature, and I should like to know whether that advantage has been offset by an increase in the capacitance of the pairs. If so, is there a corresponding increase in attenuation, and have steps been taken to deal with it, e.g. by altering the repeater spacing on the Edinburgh-Dundee cable as compared with that on the Bristol-Plymouth cable? Furthermore, does the star-quad form give rise to other difficulties? The far-end cross-talk values on the Bristol–Plymouth cable are so good at 60 kc./sec. that I am interested to know whether a similar freedom from cross-talk has been achieved on the Edinburgh-Aberdeen.

The authors stress the importance of using low-loss dielectrics for coaxial cables. The success of such cables is in fact dependent upon the dielectric losses being but a small percentage of the total losses. I should like to know the power factor of the cotopa used for the London–Birmingham cable.

Another point to which I should like to refer is the authors' very gracious reminder to us of the work done by Dr. Russell about 30 years ago, so far as the mathematics of the transmission along coaxial tubes is concerned. About 15 years ago coaxial tubes were actually used for the transmission of currents of frequency ten times as high as those mentioned in the present paper; such tubes were employed as the feeder lines of short-wave radio transmitters and receivers. There is a statement made on page 575 (vol. 81) which I think is a slip, since it rather ignores that fact, and I am quite sure the authors had no intention of doing that.

On page 587 there is a mis-print with reference to the number of 25-lb. conductor star-quads on the London–Birmingham cable—14 are mentioned instead of 6.

I have a suggestion to make in regard to Fig. 20 on page 588. Two different values of channel separation are shown in the diagram; Col. Angwin in reading his abstract of the paper made the matter quite clear, but I think a note on the diagram to show that one value is actual, whilst the other is projected, might be useful, especially to students.

Mr. F. Mercer: The paper marks a vitally important stage in the development of trunk telephony. Progress has been made in well-defined stages. First we had the dry-core paper-insulated telephone cable, next the loading coil, next the repeater, next the application of 1- to 4-channel carrier to conventional-type cables, and now the development of the special unloaded multi-channel cables described in the paper. It is a characteristic of all these developments that without them progress would have been either seriously slowed down or even completely halted.

The present obvious drawback to multi-channel systems is the necessity for close spacing of repeater stations, resulting in high maintenance costs and greater risk of breakdown. It is obviously desirable to increase this spacing, and the present limitation to this course seems to be set by far-end cross-talk and noise from extraneous sources. I should like to ask the authors whether the possibilities of using screened-pair cables have been considered. Two such cables could be used as at present, and the screening of the pairs would have the effect of eliminating far-end cross-talk due to capacitance unbalances, thus leaving only cross-talk due to electromagnetic couplings, and noise from extraneous sources. The former could be minimized to a considerable extent by cross-splicing, the well-known method used for balancing capacitance inequalities in conventional cables. Screening of pairs has the unfortunate effect of increasing mutual capacitance and therefore attenuation, but the characteristic impedance would also be reduced and correspondingly the cross-talk due to magnetic couplings. The increase in attenuation would therefore be offset by an improvement in the cross-talk characteristics, and it would appear that such an arrangement would admit operation with two cables of similar dimensions to the Bristol–Plymouth, similar spacing of repeaters (with higher gain), and greatly improved cross-

talk; or, alternatively, wider spacing of repeaters with still higher gain, and cross-talk of the same order as on the Bristol–Plymouth cable.

It would appear that the grouping of circuits is in blocks of 12 for the 12-channel cables, and blocks of 8 for the coaxial cables. Would it not be advantageous to standardize the grouping with the object of more easily linking up the two systems where this may be necessary?

With either the 12-channel or the coaxial system, failure of a cable or a repeater will have far more serious consequences than similar failure in a cable of the conventional type. Further, two cables are required in the 12-channel system as compared with one of the normal type, and the chances of failure are accordingly increased. In these circumstances it seems desirable to use rubber-wax protection as a preventive of corrosion on a much more extensive scale than has been done on conventional cables.

Captain W. Cowburn: It would be interesting to know whether the London–Birmingham coaxial cable is proving satisfactory and producing the results for which it was designed.

The authors say that in providing long-distance circuits the present tendency is to reduce the line costs but to increase the cost of equipment. I should be interested to know the relative capital costs of providing a channel by means of a coaxial cable and a physical circuit, not only as regards the capital cost but as regards the annual charges. When one considers that with the coaxial system there are repeater stations spaced at 7-mile intervals, and a considerable amount of expensive equipment at each of these stations, it seems that the capital cost is going to be considerable, but presumably not as high as providing a number of physical channels.

On the coaxial cable, alternate repeater stations only are fed with power for the valves, and the power supply is fed over the cable itself. I should like to know why that is so, and why power is not led in direct at each repeater station. In these days of extensive service by means of the grid it seems that stability could be satisfactorily obtained in this manner.

The authors exhibited a sample of crystal having a frequency of 400 kc./sec. I should be interested to learn how crystals of definite frequencies are obtained from a block of quartz.

Mr. P. Webster: The paper describes how the cost of speech channels has been lowered by using cheaper underground cables in conjunction with more expensive terminal equipment, necessitating the highest designing technique. It will be interesting in the next year or so, after operating experience has been obtained, to know whether the estimated saving has been achieved.

Multi-channel carrier telephony equipment will require maintenance by men having a higher technical training than have hitherto been employed on telephone maintenance work. In order to ease the maintenance man's burden, a considerable portion of the engineering development has been directed to the design of alarm and supervisory equipment in order to preserve continuity of service under fault conditions and to provide a ready means of fault localization.

What are the relative costs of the 12-channel carrier equipment and the wide-band carrier system utilizing a coaxial cable? Perhaps this information could be given in relation to a specific case where it is assumed that 320 speech channels are required between two points. What would be the distance between the points for which the estimated annual cost per speech channel would be the same for the two carrier systems described in the paper?

Mr. J. A. Mason: The present trend in the design of telephone systems seems to be to use the minimum amount of copper in the cable and to spend the bulk of the money on relatively expensive balancing networks and terminal equipment. Cables using audio frequencies appear to have been relegated to the class suitable only for short-distance circuits; and carrier cables in the kilocycle range, as used between Bristol and Plymouth, appear to have a wider application than those using frequencies in the megacycle range.

I understand that the present problem of the Post Office is essentially to double or treble the number of circuits available for long-distance working, and this would probably be more economically achieved by applying carrier systems to the existing trunk network than by manufacturing and installing new cables and associated terminal equipment. Indications are given in the paper that certain recent cables have been made suitable for operation on a 4-channel system, but there is no sign that the Department is undertaking any general development along these lines.

The impression conveyed by the paper is that the coaxial system is only suitable for the operation of large blocks of circuits—of the order of 300–400. The more orthodox carrier systems seem to provide for channels in groups of 12, and there would appear to be a wide field for the development of a coaxial system capable of dealing flexibly with comparatively small numbers of circuits, e.g. 100. The difficulty in this connection evidently lies in the design of the coaxial cable itself. The size of the cable is dependent on the attenuation at the highest frequency, and this in turn is dependent on the number of channels being operated, so that the smaller the number of channels the smaller the cable. Are there mechanical difficulties in the construction of a smaller cable than the one described by the authors? Their design uses an articulated outer conductor, and this may be difficult to manufacture in the smaller sizes. A design in which the insulation served to retain the circular form of the outer conductor would, I think, be more convenient for the manufacture of small cables, but the development of such cables in its turn depends upon the development of low-loss dielectrics. It would thus appear that the problem of increasing the flexibility of the coaxial system by making it suitable for smaller blocks of circuits is largely bound up with the mechanical design of the cable, and probably with the design of some almost perfect insulating material. Perhaps the authors would confirm that this impression is correct.

The present tendency in signalling over trunk lines is to employ two voice frequencies, and I should like to ask whether it is proposed to employ this method with the carrier systems.

The operation of multi-channel systems depends very largely on the use of thermionic valves, and the operating charges are very much affected by replacements of these

and hence of the life expected from them. Can the authors give any idea of the lives expected from the various classes of valve used?

Mr. T. R. Rayner: I am disappointed to find in the paper no figures as to the relative cost of providing channels in the various alternative ways, and I should like to ask whether, broadly speaking, the coaxial cable has been chosen because it is the cheapest way known to-day of providing a large block of 300 or more channels; or whether the possibility of rearranging the frequency band allocated to individual circuits and thus providing for a higher cut-off on international circuits should future developments demand this has had a considerable influence on the decision. In other words, when it was decided that a coaxial cable was the most economical method of providing the London–Birmingham–Manchester circuits were the engineers able to put on the credit side a sum representing insurance against possible future demands in addition to the demands for television channels?

One disadvantage of the coaxial cable would appear to be that in the event of damage by fire or weapons of war to the terminal equipment the complete block of circuits would be out of commission for a long period, since it would be quite impossible to patch up the circuits in a temporary manner to enable them to carry essential circuits of national importance. It would be interesting to know whether, in the event of one repeater station being destroyed, the cable can be jointed through and adjustments made to the gain at the remaining stations, so that the circuits may function even if their quality has to be lowered.

Mention is made in the paper of both balanced and unbalanced types of coaxial cable, and it would be interesting to know whether satisfactory methods are available for joining together sections of balanced and unbalanced cable and thus enabling short submarine lengths to be introduced.

I am particularly interested in the authors' mention of a method of manufacturing condensers by deposition of the metal on the dielectric; it would be interesting to learn what degree of stability is shown by such condensers with variation of temperature.

Mr. T. B. D. Terroni: The British Post Office showed courage and foresight by installing multi-channel carrier equipment so soon after the Bell Laboratories had made known their successful experiments at Morristown in 1933 and on the coaxial-cable wide-band system between New York and Philadelphia.

At the present rate of progress it would not be surprising if hyper-frequency wave guides became a commercial proposition within the next few years. There is no doubt that research developments on ultra-high-frequency transmission through hollow copper tubes with their remarkably small attenuations is being followed with close interest by communication experts; and it may well be that the not-distant future will experience the realization of a multi-channel television wave guide.

I am interested in the authors' figures of repeater gain for the 12-channel system and the wide-band system. The working repeater gain for the 12-channel system is of the order of 60 db., and this gain is presumably controlled largely by cross-talk considerations. With the coaxial system, however, the cross-talk and interference for frequencies above 0·5 Mc./sec. are entirely negligible, and the minimum level to which speech is allowed to drop is controlled by thermal noise and valve noise. The limit set to the attenuation of repeater sections at 2·1 Mc./sec. is about 50 db. This low value of attenuation for perfectly-screened wide-band systems does not appear to compare very favourably with the value for the 12-channel carrier system, and I should be glad if the authors would indicate the difference in level that obtains between thermal noise and the minimum level of the 2·1-Mc./sec. modulated carrier.

I notice that intermediate-station repeaters are operated with 250 volts anode supply, whereas terminal station equipment is operated from the normally-used battery supplies of 130 volts H.T. and 21 volts L.T. Would it not have been advantageous, as well as possibly economical, to have standardized on the higher anode-voltage basis?

The authors make no reference to phase compensation on the coaxial system. A coaxial cable of 400 miles length would involve the transmission of the modulated carrier through roughly 55 repeaters, modulators of the initial, group, and super-group type, and associated band-pass filters, having relatively sharp cut-offs. It would be interesting to know the order of the delay experienced on a circuit of this length.

Mr. J. E. Houldin: My first point is one concerning the phase correction of the repeater stages. This is of little importance for multi-channel telephony work, but is of extreme importance for television-signal transmission. Phase shift, both along the cable and through the repeater, will in general be negative at the high frequencies. If extremely large this phase shift will cause a relative movement of high lights with respect to the background in the received television image, and this will greatly impair the definition. Unless each repeater is individually corrected so that the phase shift is zero, approximately, the total phase shift throughout the cable and about 17 repeaters will be very large. Is any such correction in use in the repeaters? Fig. 21 appears to show no special corrector system.

The frequency band of the cable is 0·5 to 2·1 Mc./sec., so that special means will be needed to pass television signals into the cable. Could the authors tell me whether the method employed is as follows? The signals are modulated by a frequency of, say, 20 Mc./sec., of which the lower sideband is extracted and remodulated with a frequency of 20·5 Mc./sec., from which the lower sideband is again extracted and injected into the cable. The television frequencies will now be 0·5 to 2·5 Mc./sec.

What size of drum is the cable wound upon for transport purposes, and is the concentricity of the cable ever disturbed in transit? Is absolute concentricity essential for efficient working?

Mr. D. A. Barron: For many years now the possibility of increasing the efficiency of utilization of the frequency bands available on telecommunication channels has engaged the attention of telephone engineers. Composited, or sub-audio, telegraph working was one of the first advances, whereby the lower frequency range of 0–200 cycles per sec. on an ordinary circuit was used for telegraph transmission, the telephone band being approxi-

mately 200–3 000 cycles per sec. This was followed on the telegraph side by the development and introduction of a multi-channel voice-frequency system of telegraph working, whereby 18 duplex channels can now be provided on a 4-wire circuit, the lowest frequency being 420 and the highest 2 460 cycles per sec., with a separation between channels of 120 cycles per sec. The development of carrier-current telephony systems has proceeded concurrently with that of multi-channel telegraphy, and the British Post Office, in co-operation with the telephone companies, has for some years been developing such systems and applying them to its existing line networks.

There are single-, 2-, and 3-channel systems for 2-wire open-line circuits, the single-channel 4-wire system for lightly loaded underground cables, and others. All these have resulted in an extremely efficient utilization of the frequency ranges available on the types of circuit concerned, and enable the best possible use to be made of the older plant and of plant recently provided. This end having been achieved, it was inevitable that the next step should be to design circuits which would give us much more scope for multi-channel working than was possible on the existing networks. It is indicative of the extent of this advance to realize that in the London–Birmingham system the *lower* frequency limit which it is proposed to use, namely 0·5 Mc./sec., is nearly 10 times greater than the *highest* frequency utilized on the 12-channel carrier system, and further that one of the factors which limit the level to which speech currents can be allowed to drop, and thus determine repeater spacing, is the thermal-agitation noise of the conductors in the circuit.

The exceptional amount and value of the internal equipment associated with a coaxial-cable system, the successful working of which is wholly dependent on the good condition of the cable, is the primary cause of the "all the eggs in one basket" criticism which is frequently levelled against the system. Failure of a coaxial cable would cause interruption to many and important circuits, and it is clear that suitably-trained underground staff will need to be available in order that the promptest restoration of the service may be effected. In connection with cable failure, there are two points on which I should like further information.

Firstly, in the London–Birmingham cable, failure of the outer lead sheath would presumably not cause interruption to the coaxial cores, since they are independently protected by thin lead sheaths, and the fault could meanwhile be located by suitable tests on the interstice quads or otherwise. I understand, however, that in a modified type of cable which may be used, the inner lead sheaths are replaced by steel tapes, and it would be interesting if the authors could say to what extent this steel taping will be watertight, and thus serve to protect the cores in the event of outer-sheath failure.

Secondly, I should be glad to know whether it is proposed to attempt further to safeguard the cable by the method of keeping it constantly filled with gas under pressure—say 10–15 lb. per sq. in.—arrangements being made so that a drop in pressure actuates suitable alarms. The method is, I believe, extensively used in South America, Spain, and the U.S.A.

In connection with the Bristol–Plymouth 12-channel system, it was originally regarded as essential that the distant-end cross-talk balancing networks should be accurately located at the mid-point between repeater stations. It is stated in the paper that the location of these networks at the ends of repeater sections has been found to give results comparable with those obtained when the networks are accurately located at the mid-point. Presumably it will be standard practice in future to install the networks at the repeater stations, in view of the obvious advantage of this as against acquiring sites and erecting suitable small buildings at the mid-points.

Lastly, it appears that very comprehensive arrangements have been made for automatically switching in stand-by equipments at the terminals and also at repeater stations. I am in some doubt, however, how the fast change-over time of 30 millisec. quoted by the authors is realized. Are the valves of the spare equipment kept at the full H.T. and L.T. voltages? If not, it is difficult to see how the desired gain, and, further, the required reduction of intermodulation products, could be so quickly obtained in view of the time necessary for the cathode to reach the proper operating temperature. It would be of interest too, since these change-overs can be effected automatically at unattended stations, to know what arrangements are made for the early restoration of the main apparatus.

[The authors' reply to this discussion will be published later.]

SCOTTISH CENTRE, AT EDINBURGH, 14TH DECEMBER, 1937

Mr. J. J. McKichan: We have already completed a 12-channel carrier cable from Edinburgh to Dundee and Aberdeen, and we have 4 complete 12-channel systems working on that cable with entire success. We shall have ultimately 288 circuits, working at zero transmission loss, between Edinburgh and Aberdeen, and are quite satisfied that the correct step has been taken in adopting 12-channel carrier as the future main backbone trunk system of this country. We are now engaged in extending the system as rapidly as we can; a 12-channel carrier cable is being laid from Edinburgh to Glasgow, and another is projected from Carlisle to Edinburgh, to form an extension of a Leeds–Carlisle cable. After this 12-channel equipment has been completed we shall have 24 systems of 12 channels each from Carlisle to Edinburgh, and the same number from Carlisle to Glasgow. In a few years' time there will be a second 12-channel carrier cable from Glasgow to Edinburgh. There will thus be a triangle (Carlisle–Edinburgh–Glasgow) of 12-channel routes giving facilities for large-scale alternative routing. To serve the North, the Aberdeen 12-channel system will be extended to Inverness; a section of this cable (from Aberdeen to Huntly) has already been laid. Ultimately we shall have a main backbone system in Scotland run-

ning from Inverness southwards through Aberdeen to Edinburgh, and thence to Glasgow and the South. In a few years' time a coaxial cable may be laid from Newcastle to Edinburgh, and then we shall have as many circuits to the South as we can foresee the need for at present.

The minimum economic distance for the provision of a 12-channel carrier cable is probably about 50 miles. For shorter distances on average routes which do not require a very large number of circuits, such as the route from Glasgow to Oban, it is more economical to provide an audio cable.

To permit the higher frequencies to be transmitted the multi-channel cables described in the paper are not loaded, and since the Aberdeen cable was laid a year ago it has been found possible to dispense with balancing networks at intervals along the route. Improvements in cable manufacture enable balancing to be done at repeater-station terminals.

I should be glad if the authors would state how the power is transmitted over the central conductor of the coaxial cable to feed the valves at the amplifying stations.

Mr. H. A. Ashdowne: It is fortunate that the technical developments described by the authors have occurred, because the situation would be impossible if we had no alternative to the 800-lb.-per-mile conductor on poles or, in the future, even the 40-lb. conductor cables on an audio basis, for our long-distance circuits. The congestion under certain streets nowadays is getting as acute as it was on our pole routes of the past.

From the maintenance point of view the new developments present new problems, a new technique, and new standards; but I have no fears in that direction provided the laboratory and the field trials produce a result which does not depend upon working limits only capable of being maintained in the laboratory. Successful maintenance should be obtained, provided that the engineers in the field recruit the correct proportion of staff with the necessary knowledge and the ability to absorb the new ideas.

The authors do not mention the methods of signalling to be employed on the 12-channel and the broad-band multi-channel systems. Two-frequency signalling and dialling, which has been developed concurrently, should enable the vexed question of "transmission limits" versus "signalling limits" to be settled at the same time as the new intelligence-transmission systems are brought into service.

Some information regarding the method of terminating the coaxial cable would be appreciated. Are any special features necessary to prevent sudden changes in electrical characteristics, and on account of the current density being greatest near the inner surface of the tubular conductor?

Under "Equipment for Telephone Circuits" the authors state "It is impracticable to modulate directly up to the frequencies finally transmitted over the cables. . . ." Is this due to modulator or filter design difficulties?

The outstanding technical achievement that has made multi-channel systems possible on two pairs of conductors is the negative-feedback repeater with its remarkable linear characteristic. The authors could perhaps give an indication of the necessary power-handling capacity of the repeater for 320 to 400 channels.

With regard to through working from one multi-channel system to another, it seems a pity that we shall not be able to link up a 12-channel system to a coaxial system without introducing an audio link. If this were possible we might connect one 12-channel system containing, say, 8 working channels on the Edinburgh–Aberdeen 12-channel cable by a through amplifier to one group on the future Edinburgh–Leeds–Manchester–London coaxial cable, without reducing to an audio link at Edinburgh. This facility appears to me to be an important measure of flexibility. The simplicity and space advantages of being able to extend one 12-channel system to another 12-channel cable by only two through repeaters are, however, very great. Channels are likely to be wasted initially if only 6 of the 12 channels on one of the extended systems are required for the traffic. The initial wastage in extending a group on the coaxial system is liable to be greater.

The introduction of these new systems is creating accommodation problems. Our repeater stations are rapidly becoming too small, and we must arrange for others to relieve them. To terminate one cable of 24 12-channel systems, 72 racks are required, an average of 4 channels per rack. A coaxial cable requires about 44 racks for 320 channels, an average of 7·27 channels per rack. It therefore appears that a broad-band system is better than a 12-channel system as regards space. When a number of 12-channel systems or broad-band groups are connected "through" instead of terminated, considerably less space is required.

An interesting feature of the 12-channel system is its apparent ability to continue to function satisfactorily when the cable is what we normally regard as faulty.

Mr. H. G. Davis: The extension of the coaxial cable to Scotland is being looked forward to with very great interest by telephone engineers here. The only cable of this type in the Scottish Region at present is the one recently laid between Port Kail and Donaghadee, which is extended on a special twin concentric cable with conductors of the self-locating type from Port Kail to the amplifier building at Stranraer.

A new 12-channel carrier cable is now being laid between Edinburgh and Glasgow, and it is hoped to have circuits working in this cable by the time of the opening of the Empire Exhibition. We have a large number of 12-channel circuits working in the Edinburgh–Dundee–Aberdeen system, and they are subject to no more than the normal amount of maintenance difficulties. In these cables, it has been found necessary to set aside one pair for routine insulation testing and the detection of incipient faults. It has been found that these cables generally are well behaved, and even under what would normally be regarded as fault conditions the circuits in them still continue to give service.

In regard to transmission over the coaxial system, the most striking feature is certainly the development of the feed-back repeater. A repeater carrying without interaction some hundreds of telephone conversations, with valves working at no more than normal power-supply voltages, is in every respect a remarkable achievement. To those who, some 20 years ago, were trying to make

one repeater carry one telephone conversation successfully, the feed-back repeater represents great progress.

In the paper it is mentioned that the overall attenuation on the cable between London and Birmingham is of the order of 800 db. at 2·1 Mc./sec., and that this is subject to a deviation of 30 db. due to temperature variation. This is a large amount: if we assume a ground-temperature range of 20 deg. C. it represents a change of 1·5 db. in attenuation for every degree change of temperature. Such a figure calls for exceptional temperature correction at the repeaters. I understand that circuits varying by ± 2 db. are not good enough for television broadcasting to-day. Perhaps, therefore, the authors will give some details of the methods employed for temperature correction, and the results obtained.

When considering the extension of the coaxial and 12-channel systems to some of the more remote parts of Scotland, it has to be borne in mind that with a large number of unattended repeater stations and network huts there is a possibility of a fault at these points causing a breakdown of the system due to inaccessibility of the building after snowstorms. Careful consideration is necessary before proceeding with coaxial or 12-channel development in such areas. It may well be that for Scotland, apart from the primary routes between Glasgow, Stranraer, Edinburgh, Aberdeen, and Inverness, and the main routes to the South, audio working with attended repeater stations is still to be preferred.

Mr. J. K. Murray: It seems to me that subscribers will soon be getting on long-distance calls a stability and grade of transmission very near to the ideal, having the desirable qualities of clear articulation and uniform speech volume. Already it frequently happens with calls from London to Edinburgh that the person receiving the call in Edinburgh can hardly believe that the speaker is not in the next room. I think we shall have more and more of this appreciation by the public as time goes on, especially with the coming into operation of the highly developed trunk backbone system that has been outlined by previous speakers.

Mr. F. I. Ray: Hitherto my slight acquaintance with the theory of concentric cables has served merely to emphasize the advantages of 12-channel carrier working, while, on the other hand, the more I learnt of the latter system the more attractive appeared the use of physical pairs. From the paper and from the remarks of earlier speakers I see that this view is unduly pessimistic and that the extra complexity of cable carrier systems does not necessarily imply a greater fault liability. I must admit that my experience in the West of Scotland where 3-channel carrier systems have been employed on the aerial wires between Glasgow, Oban, and Fort William for the last 18 months has been most satisfactory, and that although faults do occur with the terminal equipment it also happens that the carrier circuits will work when the physical pairs have broken down. It is possible that there will be some similar compensation for the apparent vulnerability of 12-channel carrier and coaxial cables.

I notice from the paper that the loss in the coaxial cable between London and Birmingham is in the neighbourhood of 800 db. It is difficult to form any conception of what is meant by this figure; have the authors ever devised a simple physical comparison or analogy which would assist one to understand the significance of a ratio of this magnitude?

The reference in the paper to Dr. Russell's fundamental mathematical analysis of the characteristics of a coaxial cable reveals another of those instances in which the mathematician has been many years in advance of the practical engineer.

Finally, I would congratulate the authors on their courage in coining such a word as "coaxialibility," and would ask them what degree of coaxialibility is necessary for satisfactory working.

Mr. W. V. Ryder: What provision is made to prevent water getting into the coaxial tubes? Has any provision been made for drying the tubes with dehydrants like silica gel, and, if so, are these stored in containers near the repeater stations? Also, what effect would result from a fall in the insulation resistance of the coaxial cable due to damp? Further, are any precautions taken to prevent electrolytic trouble on coaxial cables? If such trouble occurred the sheath would corrode and very serious interruption of the public service would result.

Apparently the Post Office and the manufacturers are quite satisfied with the construction of the cable which is being provided between London and Birmingham, as it is being extended to Manchester and beyond. If a cable with coaxial cores built up in hexagonal form were employed a larger number of conductors would be available. For an increase of 0·24 in. (or 15 %) on the diameter (1·7 in.) of the existing cable, one would get 75 % more conductors. Therefore it seems to me that it would not entail any outstanding addition in cost to make provision in the new cables for a larger number of coaxial tubes.

I notice that the coaxial cable can be drawn into a 3-in. duct, and as its diameter is only 1·7 in. there must be sufficient space to take a cable giving nearly double the capacity. Increasing the diameter might, however, make it difficult to draw the cable into an existing duct.

One of the principal achievements of multi-channel carrier cable is that it enables us to meet additional traffic requirements very quickly, provided the block terminal equipments have been installed in reasonable time in advance.

Mr. F. N. Lucas: With an audio cable, when a fault occurs due to a leakage of water into it, the stage at which any circuit becomes unworkable is usually determined by "noise" (i.e. leakage of voice currents from other circuits to it over the damp paper insulation) rather than excessive attenuation. If only one circuit were working in the cable, there would be no leakage from other circuits, and it would only become unworkable when the leakage between the two wires of the circuit absorbed such a large proportion of the speech power as to render transmission excessively faint. The fault would require to be very serious before this happened. If a second circuit were working, there would be intelligible overhearing between the two circuits before this stage was reached. With a number of circuits working, the interference becomes an unintelligible chatter which masks the speech it is desired to transmit, and so renders the circuit unworkable long before the transmission loss becomes excessive.

In a 12-channel carrier cable, there will be no inter-

ference between channels in the same system due to a low-insulation fault, but only between channels in different systems having the same frequency band. So long as there are only one or two systems working in a cable, therefore, we expect to be able to work through quite a bad fault. As the number of systems working in a cable increases, however, it would appear that we again get back to the conditions we look upon as normal in an audio cable, i.e. excessive noise with only quite a small drop in insulation resistance, and the hopes which some of us may have cherished, due to the experience of working through a fault on the Edinburgh–Aberdeen cable, of relative immunity from cable-fault stoppages will be dashed. Perhaps the authors can cheer us by an assurance that my fears are ill-founded.

If they cannot, perhaps consideration of the coaxial cable may again give us heart. Except in cases of physical damage such as that caused by a pick, where the coaxial tube sustains damage as well as the outer sheath, the audio and control pairs in the interstices between the coaxial tubes will be the first to suffer. It seems probable that the warning thus given will be in sufficient time for the fault to be located and cleared before the coaxial tubes are affected to such an extent as to interrupt service. With the coaxial cable this interruption would of course be due to excessive transmission loss and not to interference between circuits.

Mr. W. V. McWalter: What is the maximum permissible power per channel which may be transmitted to the cable through the 12-channel system, and also what is the minimum permissible power per channel which may be received at the repeater on the same system?

I should like the authors' opinion on the possibility of using the spare amplifiers which are fitted at intermediate repeater stations in such a way that, in the event of a fault at any of the intermediate repeater stations, a circuit with spare amplifiers could be used to replace the faulty circuit between adjoining attended repeater stations. By this means it would, I think, be possible to bring the circuit into use more quickly than by the present method of sending men to unattended repeater stations. There are spare amplifiers at each intermediate repeater station, and by terminating cable pairs on these amplifiers and associated equalizers we should make available, between terminal repeater stations, pairs with an equivalent equal to that of the working pairs. These spare amplifiers would not necessarily have to run all the time; they could be switched in on a remote-control basis and merely brought into use when necessary.

Also, in connection with my question about permissible maximum and minimum outputs, is it at all possible—even by degrading the circuits—to use one cable for "go" and "return" pairs? This would be a very valuable asset, for in the event of one, say a "go" cable, developing a fault we could provide a skeleton service between terminals on a degraded basis by adjusting from the maximum and minimum.

Mr. H. T. W. Millar: Has the question of increasing the pressure of the air or other dielectric in the cable been considered? If the internal pressure were raised above normal atmospheric pressure it would keep out moisture to a large extent, and it would be an advantage if some form of testing apparatus were fixed to the ends of the cable in such a way that when the pressure fell an indication of a fault was given.

Secondly, is the usual complicated system of equalizers necessary on cables working at the very high frequencies mentioned in the paper?

[The authors' reply to this discussion will be published later.]

HIGH-SPEED PROTECTION AS AN AID TO MAINTAINING ELECTRIC SERVICE FOLLOWING SYSTEM SHORT-CIRCUITS

By T. W. ROSS and C. RYDER, Associate Members.

(*Paper first received* 1*st November*, 1937, *and in final form* 14*th January*, 1938; *read before the* TRANSMISSION SECTION 16*th February, and before the* NORTH-EASTERN CENTRE 14*th March*, 1938.)

SUMMARY

The interconnection of generating stations through overhead networks has not only increased the number of short-circuits but has spread their disturbing effect over a much wider area. The disturbances are of major importance when they affect rotating machines, and the degree of stability of a system immediately after a short-circuit may be the determining factor which governs the amount of power transferable over a given line. Attempts to increase this power limit by controlling the excitation of the synchronous machines were only partially successful because they did not cater for certain short-circuit conditions. It is now recognized that the most successful way of dealing with such conditions is to disconnect rapidly the faulty section and so minimize the development of angular displacement between machines in interconnected stations.

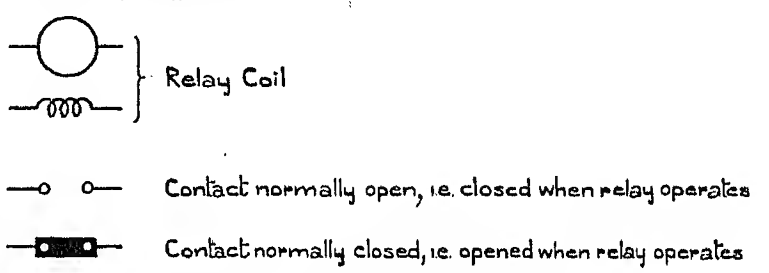
The paper reviews the various factors determining total system stability, the importance of quickly relieving the system of short-circuits, and the order of time delay which can be tolerated if system stability is to be maintained. The effect of short-circuits on load stability, and means for preventing the loss of machine load following faults, are also discussed.

After outlining the essential requirements of high-speed protection generally, descriptions of various methods and systems now in use are given.

The method of calculating the degree of stability (or instability) of a system following a fault condition is outlined in the appendices.

TABLE OF CONTENTS

TABLE OF CONTENTS—*continued*



KEY TO DIAGRAM SYMBOLS.

(1) INTRODUCTION

The interconnection of generating stations through e.h.t. networks has increased the disturbing effect of short-circuits and has intensified the desire of operating engineers for quicker fault clearance. System disturbances arising from short-circuits are solely due to the effect which the latter have upon rotating machines: such machines may be used for generating, regulating, converting, or consuming energy. Generators and synchronous condensers are regarded as the principal machines, since the "system stability" depends upon them running successfully in synchronism. Convertors and motors are looked upon as secondary plant since they do not as a rule constitute the whole of the load, nor do they control the stability of the system. These machines are affected by all faults causing a drop in voltage, with the result that they may cease to continue their proper functions when the faults are cleared and so bring about a loss of load.

The desirability of quick fault clearance has been recognized in this country since the early days of public supply, and for this reason pilot wires are largely employed in protective schemes. The cost of providing pilot wires is very often prohibitive, and it is necessary then to resort to other forms of discriminative protection. Time delay is sometimes used as a means of discrimination between healthy and faulty sections. This, however, has disadvantages, and recent developments aim at reducing the delays to a minimum. Apart from any artificial delay which is introduced there is always a small delay in the operation of circuit-breakers and

relays due to mechanical and magnetic inertia, and in providing apparatus for very quick fault clearance such delays become important.

(2) SYSTEM STABILITY

The words "system stability" are used to express a condition of stability between the major synchronous machines connected in parallel on an electric supply network. When stable conditions exist all synchronous machines will be running in synchronism, but if there is any substantial angular displacement between the rotating parts of the machines the system is unstable. The instability may be of a temporary or transient nature, in which case the angular displacement will be insufficient to prevent the machines regaining a condition of stable equilibrium. If, however, a certain limit is exceeded, a complete loss of synchronism will result and the oscillation may continue until the interconnecting circuit-breakers are tripped by out-of-step relays or by manual operation.

In general, system stability can be improved by keeping the machine and line reactance low, but in order to meet economic conditions it is sometimes necessary to adopt other methods. Quick-acting automatic voltage regulators assist in this respect since they automatically control the excitation to prevent variations in the machine flux. Voltage regulators cannot, however, improve matters beyond the ability of the exciter to respond to the need for rapid changes in output, and to assist in this respect larger exciters are now employed. This improves system regulation and enables greater changes of load to be dealt with.

It was thought at first that forced excitation was the complete solution to the problem of system instability, since the machine flux was prevented from collapsing to a dangerously low value. However, it was overlooked that during certain short-circuits synchronous ties become ineffective and a condition of instability may still arise.

Whilst a short-circuit involving three phases will cause the greatest disturbance, a short-circuit between two phases will also reduce the interchange of synchronizing power. The conditions are less severe in the case of earth faults, and voltage regulators are beneficial in minimizing disturbance.

There are many variable factors which must be taken into account when considering the change in the relative position of machine rotors during a short-circuit, and examination of the problem is greatly simplified by considering the case of two generators coupled together by a transmission line, with the network fed from one end (Fig. 1). If each generator shares the load equally the angular displacement will be a function of the tie-line impedance.

When a 3-phase short-circuit is applied across the terminals of No. 1 generator its total output becomes that represented by the energy losses in the machine. These will be sufficient to cause an overload at the instant the short-circuit is applied, and the angular velocity of the rotor will be retarded. Immediately before the fault the prime-mover will be delivering energy representing the particular load on the generator, and immediately after the fault the governor will not appreciably change this input. As the short-circuit will prevent any interchange of synchronizing power, the only other energy available for maintaining the angular velocity is the kinetic energy of the rotors. This, together with the steam input, is insufficient to prevent initial retardation, but as the current decays the losses decrease rapidly and the machine commences to accelerate. As we are confining our study to the conditions existing immediately following the short-circuit, neither voltage regulator nor governor action enters into the problem.

Because of the impedance of the tie-line the current and power outputs of generator No. 2 will be somewhat lower than those of generator No. 1. Consequently the rates of change of angular velocity of the rotors will be different, and if the tie-line impedance is sufficiently great the rotor of machine No. 2 may immediately commence to accelerate. The relative impedance between the machines and the fault is thus an important factor in determining the angular positions of the rotors during the initial stages of the short-circuit.

Synchronous condensers used for line regulation must be considered as part of the major plant on a supply network, and as such their performance during system faults must be studied. These machines have no prime mover to assist in maintaining speed during short-circuits, and generally they have less inertia than generators, with

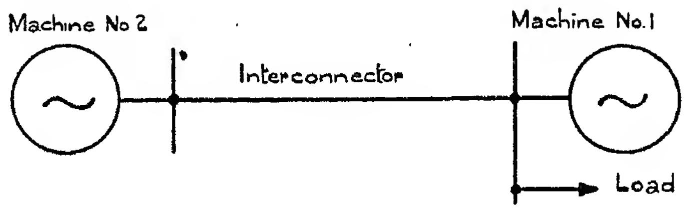


Fig. 1

the result that a greater angular displacement may occur in a given time. The lower inertia is an advantage during minor disturbances such as faults to earth or faults which do not entirely prevent an interchange of synchronous power; but if the synchronous tie between machines is either broken or rendered ineffective the lower inertia is a disadvantage.

(a) Effect of Short-Circuit Time Factor

If there were no delay in clearing a fault there would be no change in the rotor positions, but since this is not possible it is necessary to establish what order of angular displacement is acceptable. The maximum angular displacement which can be allowed between the various rotors without risk of instability largely depends upon the impedance of the interconnecting circuits, and will vary for different network conditions. It must be remembered that the conditions which matter are those existing after a fault has been cleared, since the removal of a faulty section may increase the impedance between certain machines. Although it is possible for field-forcing to affect a particular case, it is generally accepted that stability is not endangered provided the angular displacement does not exceed 100 electrical degrees.

The problem therefore is to determine the time allowable for short-circuits to remain on the system without the displacement between the machines having exceeded this angle; as an aid to this the curves in Figs. 2 and 3

have been drawn. These curves are the results of calculations from design data for average 3-phase turbo-generators, and show the angular displacement of the rotor with varying time and short-circuit conditions. In producing the curves the following assumptions have been made:—

Machines are of equal output and are running fully loaded.
The transient reactance of each machine is 10 %.
The machine governor-setting remains at full load during the time period under consideration.
Field-forcing is not employed.
The short-circuit occurs at the instant giving maximum asymmetry.
The machines are connected as shown in Fig. 1.

The curves show the angular displacements of the rotor from its initial position under varying fault conditions, and with a knowledge of the impedance between each machine and the fault the relative positions of the two rotors after a given time can be determined.

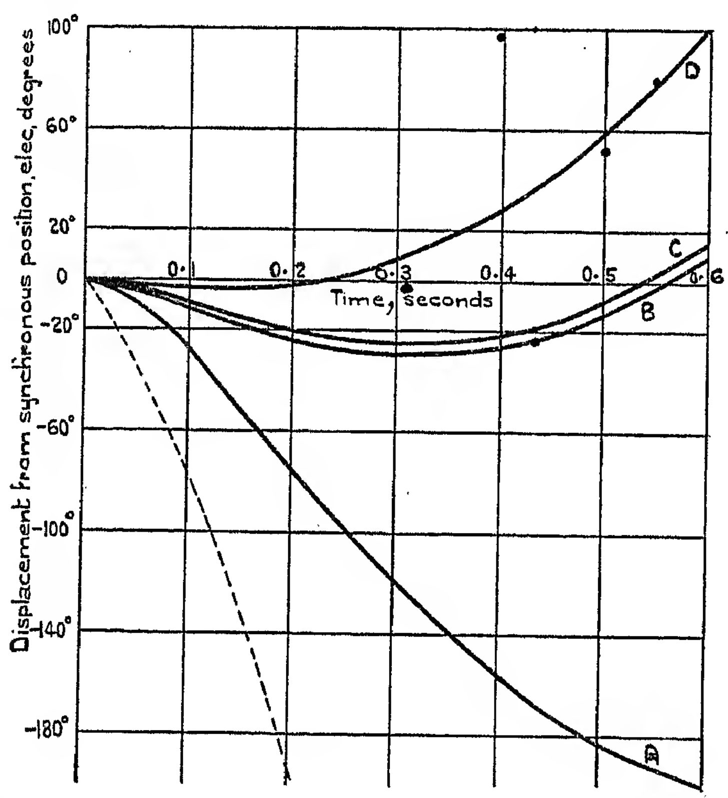


Fig. 2.—Curves showing relations between generator rotor displacement and time for various conditions of 3-phase faults imposed.

Curve A.—Total fault loop reactance = 10 %.
Curve B.—Total fault loop reactance = 20 %.
Curve C.—Total fault loop reactance = 30 %.
Curve D.—Total fault loop reactance = 40 %.

The initial load angle between machines is not included in the curves, because the effect of this on the ultimate angle of relative displacement will vary according to the position of the short-circuit. For the purpose of the present consideration, assume that at full load the angle between the two rotors is not greater than 15° (electrical), representing a reactance of 25 % between the machines. Having made this assumption it is possible to determine from the curves how far apart the rotors will swing for varying fault conditions. In the case of the most severe short-circuit (i.e. involving all 3 phases and close to the generator) the allowable time delay would appear to be 0·25 sec. if instability is to be avoided. In cases where the impedance of the synchronous tie is considerably increased as the result of disconnecting a faulty section it may be necessary to decrease this time.

Fig. 2 includes a dotted curve showing the typical angular displacement of a synchronous condenser rotor when a 3-phase short-circuit is applied across its terminals. This curve indicates that when the short-circuit entirely prevents an interchange of synchronizing current, synchronous condensers will decelerate at a quicker rate than generators. This represents the worst possible conditions and it is doubtful if such a fault would be cleared without loss of synchronism. Under other circumstances where the voltage is not reduced to zero it is more probable that a synchronous relationship with the generator will be maintained for a longer time, and for practical purposes the order of tripping time can be considered as being similar to that for generators.

(b) Load Stability

The load supplied from an electric supply system usually consists of a combination of rotating machinery and stationary apparatus. A line short-circuit which causes a drop of voltage at the terminals of the rotating machines will to some extent disturb the normal running conditions. If the short-circuit is in such a position that the voltage falls considerably, a machine will slow down at a greater rate than it will do if the voltage-drop is comparatively small. The rate of deceleration will also depend upon the nature of the load on the machine and on its ability to return energy to feed the short-circuit.

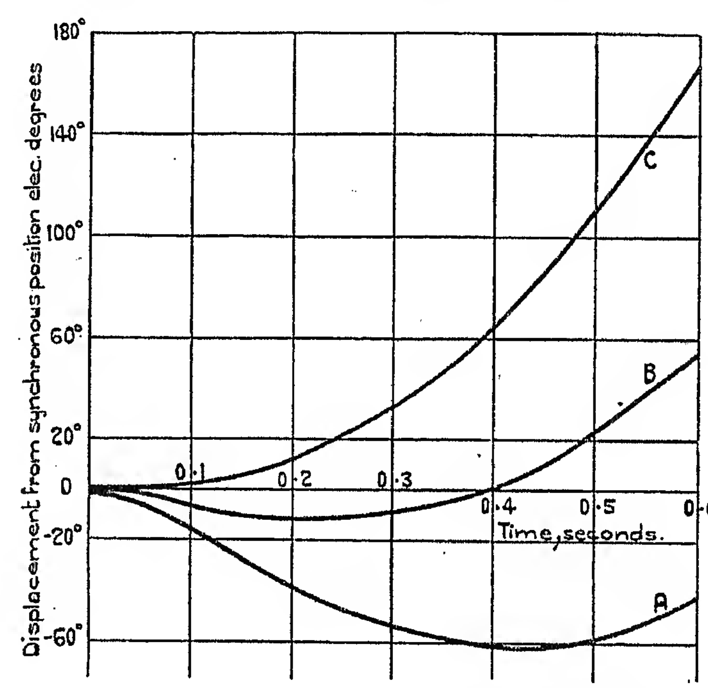


Fig. 3.—Curves showing relations between generator rotor displacement and time for various conditions of 2-phase faults imposed.

Curve A.—Total fault loop reactance = 20 %.
Curve B.—Total fault loop reactance = 40 %.
Curve C.—Total fault loop reactance = 60 %.

Network faults, therefore, should be removed as quickly as possible, but even then other precautions are necessary if loss of load is to be avoided. These precautions are very seldom taken, and most of the gear in use causes unnecessary disconnection of healthy machines.

When the short-circuit has been removed and the voltage recovers, the rotating load should automatically resume normal speed. Certain classes of machines do so

more readily than others but require a considerable increase in current. Overcurrent protective devices should be designed to allow for this increase, to give the machines a chance of remaining in service.

Any arrangement for cutting out the overcurrent trips during starting of machines is not satisfactory, and thermal-type overload devices do not adequately protect against damage due to short-circuits in the machine windings, etc. Probably the most satisfactory protection for motors is a tripping device which is insensitive to positive phase-sequence currents, but sensitive to negative and zero phase-sequence currents. The former predominate during all normal conditions, including starting and low-speed periods, but electrical faults produce negative or zero phase-sequence currents.

Thermal protection is suitable for preventing damage to the windings due to mechanical overloading.

Another prolific source of unwanted tripping is the under-voltage coil with which many motor starters and circuit breakers are fitted. These coils are usually of the instantaneous type, and a momentary drop in voltage will very often bring about the disconnection of a machine which would otherwise have remained in service. It is highly desirable, therefore, that all under-voltage releases, if such are considered necessary, should have a delayed action.

A delayed action on reverse-current trips for rotating convertors is also an advantage and often prevents the loss of such load following momentary reductions in the a.c. supply voltage. It should be remembered that delay increases the possibility of the machines flashing over at the d.c. end or running up to an excessive speed when the a.c. supply fails entirely. Hence delayed action for reverse-current trips should be applied with care, and the time delay should bear some inverse relation to the reverse current. Relays constructed on this principle are available and have proved quite successful in practice.

With such precautions most of the machines constituting an industrial load will successfully remain in service in spite of the most serious network short-circuits, although the latter may not be cleared as quickly as might be desired. The machines which are most likely to give trouble are synchronous motors and convertors, and where these are concerned excessive delay in clearing short-circuits will cause them to drop out of step. The order of time delay which will not cause an undesirable disturbance to such a load will, in general, be not less than that which has been found necessary for system stability.

(c) Back-Up Protection

A very common practice is to provide time-delay overcurrent relays as back-up to the quick-acting unit-type protection. Such a practice may, however, lead to complications, since these relays can operate on the heavy synchronizing currents which flow between synchronous machines following a system fault. The tie between the machines is thus broken, and this prevents them regaining a state of stable equilibrium where otherwise they might do so. If back-up protection is installed this should preferably be of the time/distance measuring type with a setting to cover at least two sections of network. Failing this, the overcurrent relays should have a time delay sufficient to cover the oscillating period, plus the fault-clearing period. The authors have experience of cases where overcurrent relays have caused unnecessary dislocation following the successful clearance of a short-circuit, and this form of back-up protection, whether for use on generators, transformers, feeders, or busbars, must be carefully applied, keeping in mind that synchronizing currents may sometimes reach several times full load of the machines in question.

(3) HIGH-SPEED PROTECTION

(a) Circuit-Breakers

Mention has already been made of high-speed circuit-breakers and it is obvious that the speed of the circuit-breaker is a very important factor in high-speed protection. Special circuit-breakers are now available which can clear a short-circuit in 0·06 sec., but, as already indicated, such speedy operation is not always necessary. Conventional oil circuit-breakers usually can be modified so as to decrease the tripping time, and in this way times

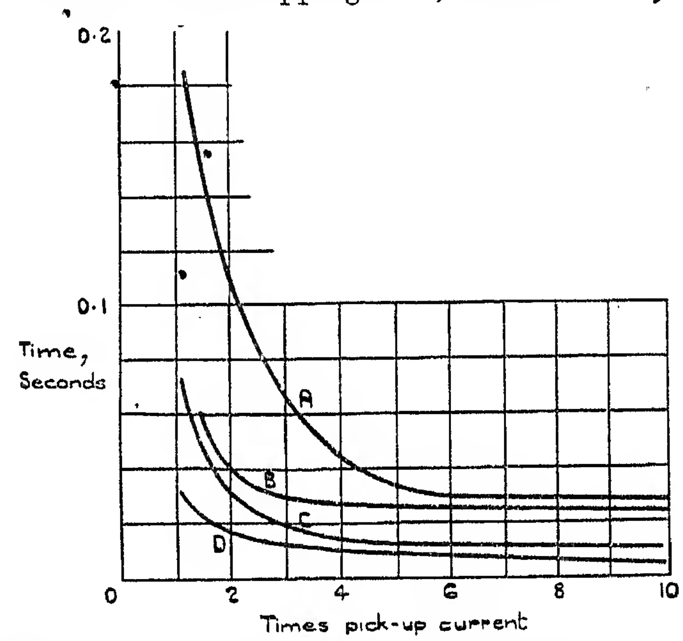


Fig. 4.—Operating-time/current curves for typical forms of high-speed protective relays.

Curve A.—High-speed Translay relay.
Curve B.—Differential beam relay.
Curve C.—High-speed directional relay.
Curve D.—Attracted-armature type overcurrent relay.

of the order of 0·12 to 0·16 sec. are obtainable. Arc-control devices have materially assisted in this respect, but other modifications such as stronger springs, lighter mechanisms, and forcing of the magnetic circuits of the tripping electromagnets, help in obtaining higher speed. Magnetic forcing may be accomplished by increasing the tripping current, and in most cases high-speed auxiliary tripping relays will be required to deal with these larger currents.

(b) Protective Relays

The time taken to clear a short-circuit includes that of the relay or relays to energize the trip coils of the circuit-breakers. If the fault must be cleared in, say, 0·25 sec. and the circuit-breaker takes 0·16 sec., then the relays must operate in less than 0·09 sec. In the same way a fault-clearance time of 0·15 sec. with a circuit-breaker taking 0·08 sec. leaves 0·07 sec. for the relays. Since on certain protective schemes two or more relays sometimes

have to operate in sequence, the individual relays must be much quicker than this, and relays having an operating time of less than 0·02 sec. have been developed. Fig. 4 shows typical time/current curves for such relays.

Experience has shown that magnetic inertia is an important factor in the times taken to operate high-speed relays, and to reduce this to the smallest practicable value it is necessary to force the magnetic circuit by increasing the ampere-turns. It is, however, impossible to eliminate entirely the time delay, and so-called high-speed relays have a certain delay which varies inversely with the operating current. As the magnitude of the fault current can in general be taken as an indication of the disturbing effect of the short-circuit, the slower operation at lower current values is not a serious disadvantage.

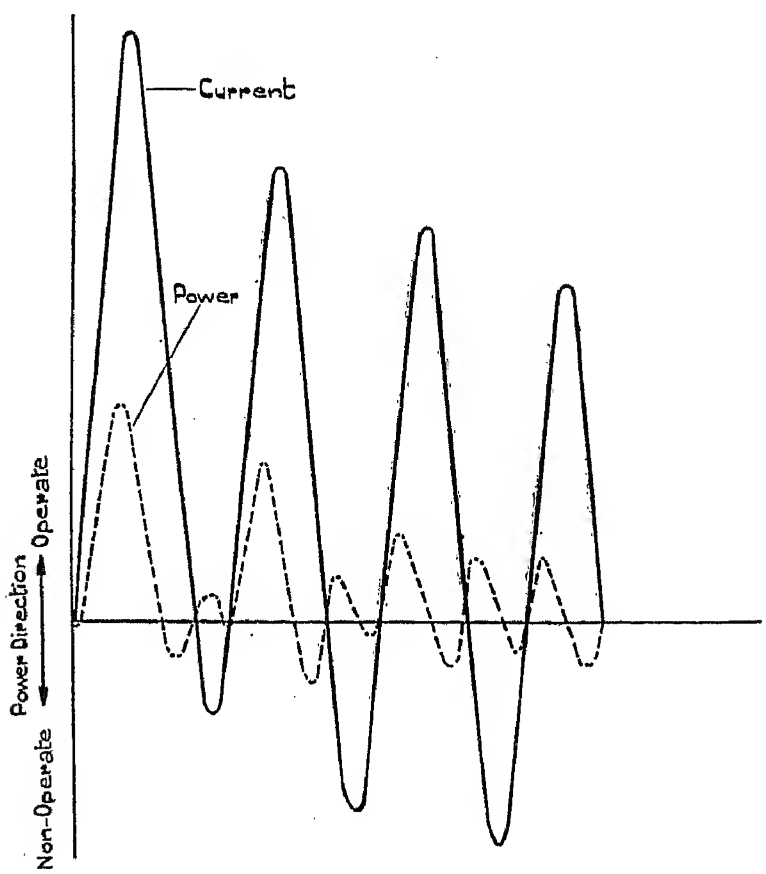


Fig. 5.—Relation between asymmetrical current and power in the region of 0·25 power factor, showing that the direction of asymmetrical power is such as to assist normal operation of a directional relay.

Where directional relays are required it is usual to design them to operate on a very small fraction of normal full load, so that they will function quickly although the system voltage, and consequently the motive power, are low during short-circuits. It is desirable, however, that the relays should remain in the inoperative position during normal conditions and so avoid the possibility of a race between them and the operation of the fault-detecting relays. This can be done by providing the directional relays with a voltage element which will develop a backward torque on the relay movement. This torque will be proportional to the square of the system voltage and will be sufficient to hold the relay against the torque developed by the wattmeter element during normal load, but will be insufficient to hold it during short-circuits when the voltage is low.

Asymmetrical current conditions during the initial stages of a fault do not appear to have any deleterious effect upon the operation of induction-type directional relays. Fig. 5 shows a pronounced asymmetrical current with a correspondingly distorted power wave for a power factor in the region of 0·5 when steady conditions prevail. In effect the asymmetry increases the apparent power factor, thereby increasing the relay torque in the direction of normal operation; this has been borne out by numerous tests. Because of this it is possible to utilize relays having operating times approaching a half-cycle.

One of the objections to very quick relaying was that it might cause the loss of healthy sections due to transient conditions which accompany short-circuits on other parts of the network, and it has been the practice in the past to introduce a slight artificial delay to overcome this difficulty. It is obvious that any attempt to speed up relay operation will not be successful unless accompanied by means of preventing unwanted tripping. The means employed by the authors will be described later when the various protective schemes are dealt with.

(4) PROTECTIVE SYSTEMS

There are three methods, all of which are suitable for high-speed protective gear, by which discrimination between healthy and faulty sections of a network may be obtained:—

(*a*) Differential or balance method.
(*b*) Locking method.
(*c*) Distance-measuring method.

These methods are well known, but when applied to high-speed protection certain modifications are necessary to decrease the operating time and to prevent tripping of circuit-breakers controlling healthy sections or apparatus.

(a) Differential or Balance Method

This method consists of means for comparing the current which enters and leaves the protected zone, or for comparing the currents flowing in two parallel circuits. Because of the speed which is required, the comparison must be made during the first cycle or so after the short-circuit, at which time the current wave may be displaced with respect to its zero. This would not introduce any complications were it not for the current transformers, which will not function in the normal manner to produce secondary currents to coincide in phase and magnitude with asymmetrical primary currents. The difference is due to the large unidirectional component of the fault current, which builds up a magnetic flux in the secondary load at a rate depending upon the time-constant of the secondary circuits. As the rates at which these fluxes rise will probably differ, the corresponding secondary currents may not balance against each other. Such transient unbalance has been found to exist in practice and it is necessary to design the protective gear so that it will not cause tripping on through faults but at the same time will maintain its high speed when clearing short-circuits. The most satisfactory method of ensuring that high-speed differential protective gear will remain stable during through-fault transient conditions is to incorporate an electrical bias which increases with the magnitude of the through-fault current. This has the additional

advantage that it compensates for unavoidable variations in the normal characteristics of current transformers or any other temporary unbalance in circuits which may have to carry heavy through-fault current.

In the protection of single feeders, the difference between the magnitude of the current entering a healthy feeder and that leaving the feeder, due to line capacitance, may become of consequence. This difference, though unimportant at normal frequencies, may cause incorrect operation of relays at the higher transient frequencies which arise during or immediately after short-circuits. To obviate incorrect operation from this cause, an electrical bias feature is used, the torque due to which increases with frequency.

If the differential scheme is of the opposed-voltage type as distinct from the circulating-current type, it is necessary to prevent operation due to charging current in the pilot wires. As the latter will not reach a dangerous magnitude unless the feeder is overloaded, the current-

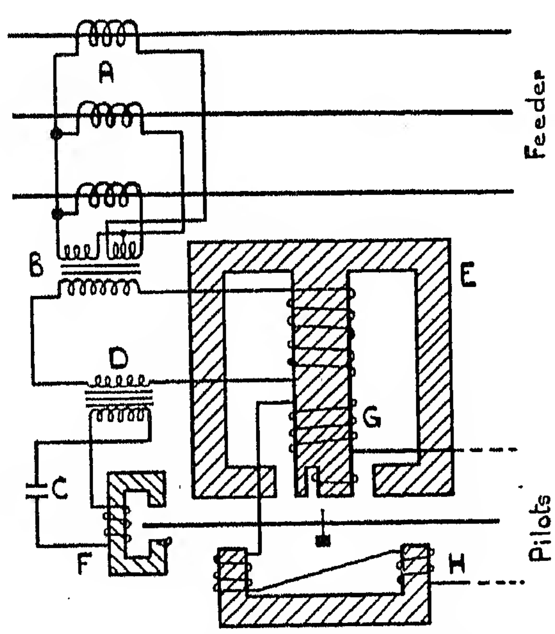


Fig. 6.—Schematic diagram showing method of high-speed feeder protection using Translay-type relays.

A = Line-current transformers.
B = Auxiliary summation transformer.
C = Capacitor.
D = Auxiliary transformer.
E = Translay-type relay having operating windings G and H and biasing element F.

bias feature already mentioned will be effective in overcoming this difficulty. Figs. 6 to 12 (inclusive) indicate the methods used by the authors for various kinds of differential protection. It will be noted that in some schemes summation current-transformers are used. This is done for three reasons: (*a*) To reduce the number of relays; (*b*) to provide a bias current from any or all phases; and (*c*) to increase the winding space available on the relay electromagnets. Such arrangements are, usually, not possible when power transformers are included in the protected zone, and it is then preferable to have one relay per phase in order to obtain a balance of the secondary currents during through faults.

(i) Pilot-Wire Differential Protection for Feeders.

High-Speed Translay Relay Scheme.—Fig. 6 shows (diagrammatically) typical connections of a high-speed Translay type relay for the protection of a single feeder.

The Translay* relay E is energized from the three line-current transformers A through the auxiliary summation transformer B. This latter also supplies the frequency-biasing transformer D, the secondary of which feeds the winding F through a series capacitor C. The equipment at the remote end of the line is identical.

During normal or through-fault conditions the voltage induced in windings G is equal and opposite to that across the corresponding winding on the distant relay, and little or no current flows in coil H and in the pilot wires, so that the relays are inoperative.

On the occurrence of a fault on the protected feeder, the currents entering and leaving the feeder no longer balance, causing a current to circulate through the pilot circuit to operate the relays.

The frequency-bias element increases the stability of the relay during conditions producing high-frequency transients, since the impedance of the capacitor decreases with increasing frequency, thereby permitting a greater current to flow through its coil.

High-Speed Beam Relay Scheme.—This is an alternative to the Translay scheme of feeder protection, using pilot wires. The schematic diagram of connections,

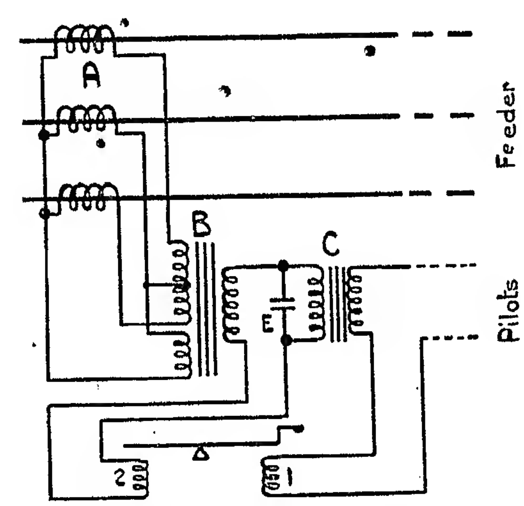


Fig. 7.—Schematic diagram showing method of high-speed feeder protection using beam-type relays.

A = Line-current transformers.
B = Auxiliary summation transformer.
C = Auxiliary transformer.
E = Capacitor.
1 and 2 = Operating and restraint coils, respectively, of beam relay.

Fig. 7, shows the relay-operating coil 1 connected in series with the pilot-wire circuit and the secondary winding of an auxiliary current-transformer C. The primary of this transformer is supplied from the summation current-transformer B which also supplies the relay bias winding 2. The stability of the relay under high-frequency transient conditions is increased owing to the action of the capacitor E which reduces the input to the operating transformer C.

Normally, and also during through-fault conditions, the secondary voltages of the auxiliary transformers C at the two ends of the feeder are equal and opposite and very little current circulates in the pilot wires and in the relay-operating coils 1. Furthermore, the relay is held in the inoperative position by the current flowing through the primary winding of transformer C and coil 2. The occurrence of a fault on the protected feeder section will

* See Bibliography, (7).

cause the voltage balance in the pilot circuit to be upset, a current will circulate, and the relays at each end of the feeder will be operated.

(ii) Differential Protection for Parallel Feeders.

High-Speed Beam Relay Scheme.—Fig. 8 shows the connections for the equipment at one end of the feeders for protecting duplicate parallel feeders using beam relays; the equipment at the other end of the feeders is identical except for the addition of directional relays when necessary.

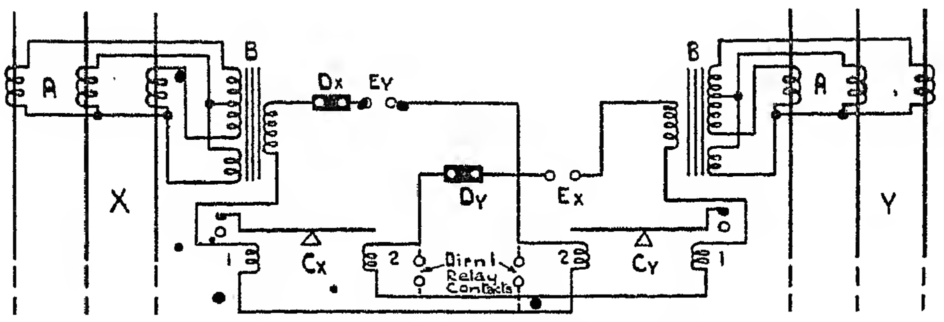


Fig. 8.—Schematic diagram showing method of high-speed parallel feeder protection using beam-type relays.

A = Line-current transformers.
B = Auxiliary summation transformers.
C = Beam-type high-speed relays having operating coils 1 and restraint coils 2.
D = Contacts of high-speed auxiliary relays or tripping relays.
E = Auxiliary contacts on feeder circuit-breakers.

The line current transformers A in each feeder are connected to summation transformers B, the secondaries of which feed the biasing and operating coils of relays C.

When both feeders are healthy, the relay associated with either is biased against operation by the summated load currents of the other, and both relays are inoperative. When one feeder (say Y) becomes faulty, the secondary current will cause relay Cy to operate and in addition will give rise to a larger restraint bias to relay Cx on the healthy feeder.

If directional relays are provided they should preferably be of the type which remain inoperative when the power carried by each feeder is equal in both magnitude and direction.

In the event of a fault occurring on one of the feeders the associated directional relay will close its contacts to short-circuit the bias coil on the beam relay controlling the faulty circuit. The latter relay is then free to operate although the fault current in each of the feeders is equal in magnitude. Such a condition will occur at the receiving end of two parallel feeders.

To prevent tripping of the healthy feeder when the faulty feeder is cleared, a high-speed relay D is energized in parallel with the trip coil of the faulty feeder circuit-breaker. The contacts D of this relay interrupt the operating-coil circuit of the sound feeder relay until the auxiliary switch E of the faulty feeder circuit-breaker opens.

High-Speed Translay Relay Scheme.—Whereas the bias beam-relay method of parallel-feeder protection can be applied only to systems of two parallel feeders, a scheme using Translay relays may be applied to systems of any number of parallel feeders. The general operation of this scheme is as previously described* but with the additions of auxiliary summation transformers and high-speed d.c. relays functioning as described for the method shown in Fig. 8.

* See Bibliography, (7).

(iii) Differential Protection for Transformers and Transformer-Feeders.

Owing to the large equivalent variation which may exist between the primary and secondary currents of a power transformer during switching or through faults, it is impossible to apply high-speed differential protection unless the current at which the relays will operate is greater than the maximum difference which may occur. At the same time, the transformer must be protected against faults which may not allow this comparatively large current to flow.

A satisfactory method of overcoming this difficulty is to use two differential relays, one having a low current setting with an inverse time-delay feature, and the other a high current setting but with high speed of operation. Fig. 9 shows the arrangement of such a scheme, the differential induction-pattern relay A being low set and giving the characteristic a–b on the time/current curve Fig. 11, while the high-set relay B, of the high-speed beam type, effects portion b–c of the curve. Fault currents of a low value are dealt with by the slower relay, while higher values operate the high-speed relay.

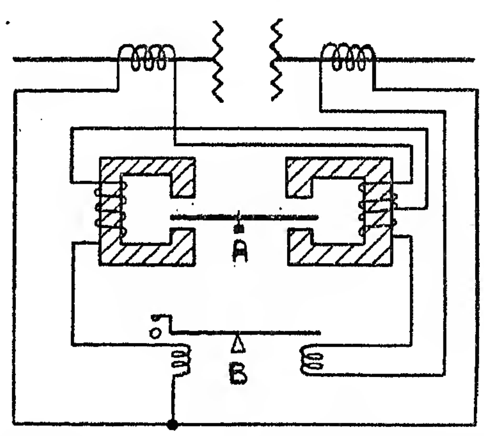


Fig. 9.—Schematic diagram showing system of high-speed differential protection for transformers.

A = Differential induction-type relay.
B = Beam-type relay.

Similar problems to those mentioned above occur in the case of transformer-feeders; in addition it may be necessary to include some arrangement for intertripping

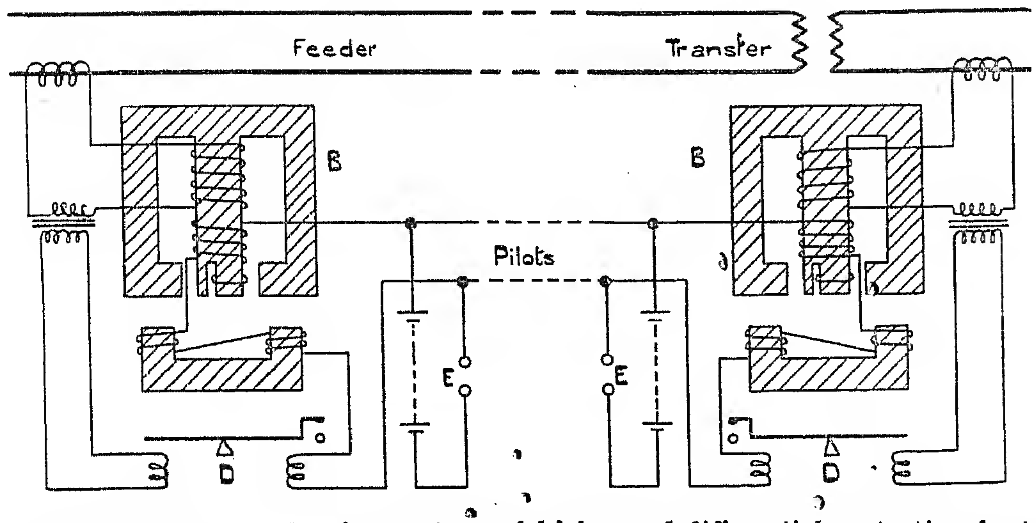


Fig. 10.—Schematic diagram showing system of high-speed differential protection for transformer-feeders with intertripping.

B = Translay-type relay.
D = Beam-type relay.
E = Contacts of high-speed auxiliary relays or tripping relays.

the circuit-breakers at each end. In the method shown in Fig. 10 Translay relays and beam-type differential relays are applied to give the lower- and higher-speed characteristics respectively, while d.c. pilot injection is employed for intertripping.

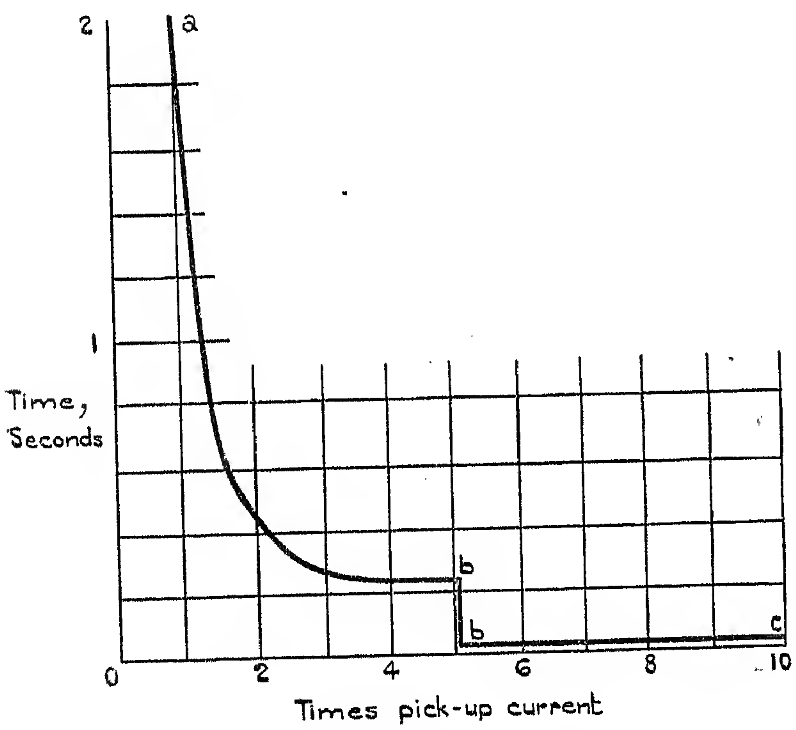


Fig. 11.—Typical time/current curve for the differential methods of protection for transformers and transformer-feeders as depicted in Figs. 9 and 10.

Curve (a — b) effected by induction relay.
Curve (b — c) effected by beam relay.

Normally, the Translay relays B at each end of the line develop equal secondary voltages and the pilot circuit is voltage-balanced. On the occurrence of a feeder or transformer fault, depending upon its magnitude, either the Translay relay B or the beam relay D will operate, since the secondary voltages of the relays at each end of the feeder will be different and a current will circulate in the pilot-wire circuit. Energized in parallel with the circuit-breaker trip coil is the coil of a high-speed d.c. relay, the contact E of which closes and connects the intertripping battery to the pilot lines. The direct current flowing in the pilot circuit causes the beam relay at the remote end to operate, thus tripping the remote circuit-breaker.

Although Fig. 10, for simplicity, shows the arrangement of relays, etc., for a single-phase feeder, the method can be applied to 3-phase transformer-feeders, when three Translay relays and three beam relays would be used at each end, coupled together by three pilot wires.

(iv) Earth-Fault Protection for Machines and Transformers.

Fig. 12 shows two methods of application of beam relays to the protection of transformers against earth faults. Method (*a*) is for the protection of machines or

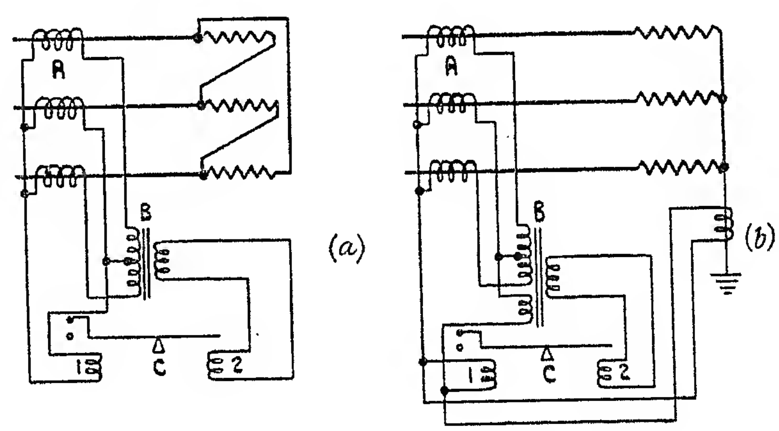


Fig. 12.—Schematic diagrams showing methods for high-speed earth-fault protection.

A = Line-current transformers.
B = Auxiliary summation transformer.
C = Beam-type relay having operating coil 1 and restraint coil 2.

transformers where no neutral point is available, and method (*b*) is applicable to machines and transformers which have their neutral point earthed. In both methods the relay is biased by the summated line currents and is operated by the residual earth-fault current.

(b) Lock-in Methods of Protection for Feeders

In these systems of protection the circuit-breakers at one end of a protected zone are prevented from tripping on through faults by a locking signal controlled by directional relays at the other end of the zone or in the zone

immediately beyond it. For instance, in the case of a feeder where fault current flows into the busbar, a directional relay would send a signal through some communicating channel to lock-in the circuit-breaker at the distant end of the feeder. If, however, the feeder itself is faulty, the signal will be interrupted and the circuit-breaker will be allowed to trip and clear the fault. If fault current is fed in at both ends then both circuit-breakers are allowed to trip.

One of the difficulties associated with lock-in schemes is to prevent tripping during system oscillations which might cause momentary overlapping of the directional relay contacts at the two ends of the protected zone.* Such oscillations frequently occur immediately following the clearance of a short-circuit, and are the results of the recovery of the synchronous relationship between machines. If the synchronizing current exceeds the setting of the fault-detecting relays, at first the gear is prevented from tripping by the locking signal which is controlled by the directional relay at one end. As the resultant power oscillates, the directional relays will change their relative positions and transfer the control of the locking signal from one to the other twice during each oscillation; these oscillations have a frequency of about 1 cycle per sec. If there were zero impedance between the two relays they would change over at precisely the same instant, but owing to the line impedance there may be a short overlapping of the contacts, during which time the locking signal will be interrupted. This period can be bridged over by a relay having a short time delay in closing and opening. Its operating coil is energized only when power is flowing out of the feeder with an excess current in all three phases, and its contacts are so connected that they maintain the locking signal for a short period after the directional relay at that end attempts to interrupt it.

(i) Pilot-Wire Lock-in System.

A scheme developed for this purpose utilizes non-directional fault-detecting relays of the overcurrent or impedance type, which, during fault conditions, initiate the locking signal on all circuits carrying fault current. The functioning of directional relays will then cause the signal to be interrupted where circuit-breakers carry fault current away from the busbar, and those controlling the faulty section will trip. Fig. 13 shows this scheme applied to a feeder having a pilot wire or telephone circuit for the conveyance of the locking signals. The fault-detecting relays 1, 2, 3, and 1A, 2A, 3A, are shown as overcurrent relays but they may be of the distance-measuring type. The directional relay 5 (operating coils not shown) is a high-speed wattmeter type having a d.c. restraint coil 5X which is normally energized from the battery and holds the relay in the position representing power flowing out of the feeder. An important feature of the scheme is that the operation of the various relays is sequential and does not depend upon the speed of individual relays for discriminating purposes.

The scheme operates as follows. Immediately a short-circuit occurs, the fault-detecting relays 1, 2, or 3, operate. One of their circuit-closing contacts causes the pilot-energizing relay 4 to pick up and energize the pilot wires

* See Appendix 3.

and signal-receiving relay 9; one contact on this latter controls relay 4X which has a self-sealing contact. The circuit-opening contacts of relays 1, 2, and 3, are connected in series and de-energize the restraint coil 5X of the directional relay. Fault current flowing into the feeder causes directional relay 5 to open two contacts and to close a third contact. In turn, relay 4 and the pilot-wire circuit are then de-energized. If the fault is external to the protected line section, relay 9 will still be maintained operated from the distant end and thus prevent the closing of relay 6 and the operation of the second set of fault-detecting relays 1A, 2A, or 3A. If, however, the fault is on the feeder, relay 9 will be de-energized; this permits relay 6 to pick-up and allows the relays 1A, 2A, or 3A, to operate and complete the tripping circuit.

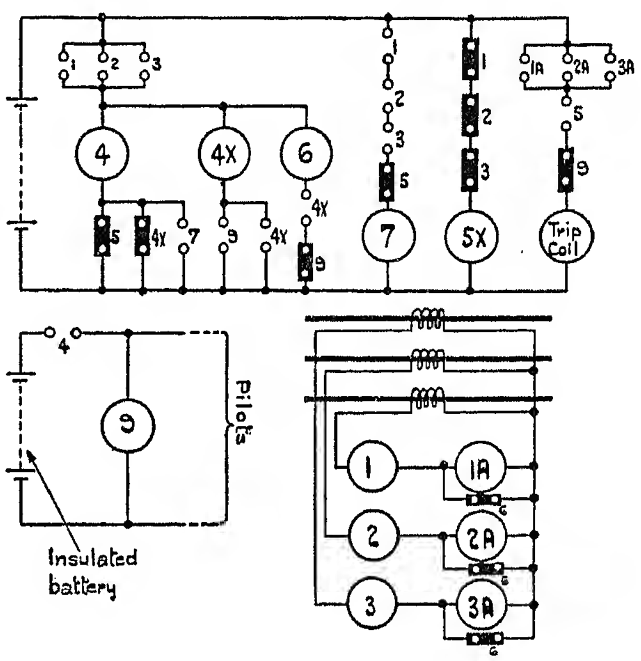


Fig. 13.—Schematic diagram showing method of high-speed pilot-wire lock-in feeder protection.

1, 2, 3 = Low-set fault-detecting relays.
1A, 2A, 3A = High-set fault-detecting relays.
4 = Pilot-energizing (insulating) relays.
4X = Auxiliary relay.
5 = Power directional relay having restraint coil 5X.
6 = Auxiliary relay.
7 = Surge-guard relay.
9 = Signal-receiving (lock-in) relay.

Relay 7 is the surge-guard relay which has a delayed opening action to prevent operation of the gear during system oscillations. Its function is to continue the signal current for a short time after it would have been discontinued by the directional relay 5 during a system oscillation. To prevent interference with legitimate operation during 3-phase faults, the relay has also a delayed closing action.

(ii) Carrier-Current Lock-in Protection for Feeders.

If it is difficult or impossible to obtain as a signal channel a pilot or telephone circuit, carrier-current signals superimposed on the power lines may be employed. Carrier-current relaying was first used in the United States some 12 years ago, but at that time the locking principle had not been developed and selective action was obtained by other means. The original schemes were not very satisfactory and it was not until the locking principle was used that carrier-current relaying was found to be practical. Many installations are now operating

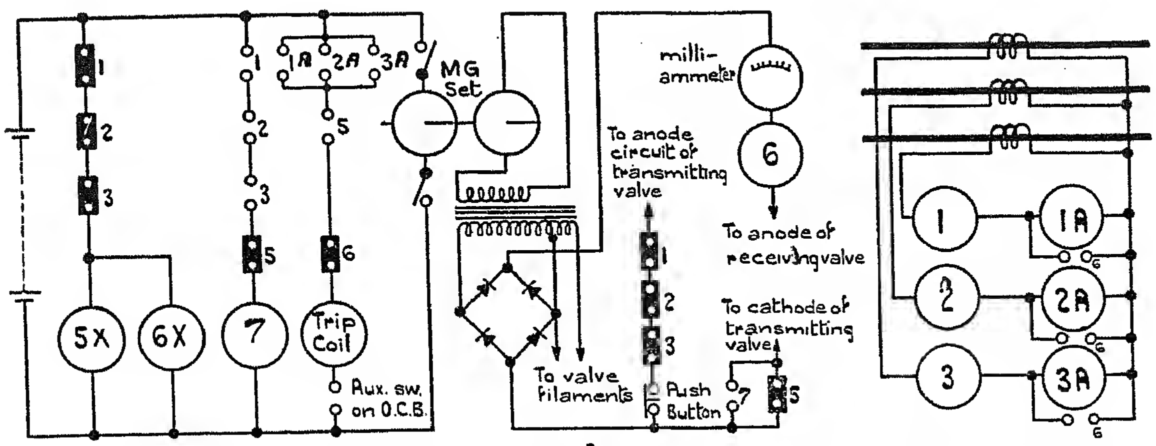


Fig. 14.—Schematic diagram for high-speed carrier-current lock-in protection.

1, 2, 3 = Contacts on low-set fault-detecting relays.
1A, 2A, 3A = Contacts on high-set fault-detecting relays.
5 = Contacts on power directional relays.
5X = D.c. restraint winding on directional relays.
6 = Carrier-receiving relay.
6X = D.c. restraint coil on relay 6.
7 = Surge-guard relay.

successfully in America,* and this type of protection is rapidly taking the place of other methods when pilot circuits are not available.

To reduce the cost of the terminal apparatus, frequencies of the order of 100 kc. are used for transmitting the signals from end to end of the protected section. The high frequency is generated by a thermionic-valve oscillator, and other valves are used to receive the signals and render them suitable for use on electro-mechanical relays. The high-frequency current is fed into the lines through static capacitors, the frequency at each end being similar. Rejector choke coils (sometimes termed " line traps ") are provided at each end of the line to confine the signal currents to their particular section. As the line traps cannot have an infinite impedance the carrier frequencies for adjacent sections must differ sufficiently to prevent any overlapping of the signals from one section to the next. Generally, the original frequency may be reverted to on the third consecutive section.

To avoid delay in sending or receiving locking signals the valve cathode heaters must be continuously energized whenever the power line is in service. In most cases an arrangement is provided by which the operating staff may check the continuity of the carrier channel as often as desired. This has been found to work out very well in practice; if the signal strength is measured each time the test is made any deterioration of the apparatus is detected before it can cause trouble. The signal strength is measured by a milliammeter at the receiving end or, where the substations are unattended, by a current-measuring relay which will send a return indication if the signal strength is above a predetermined level.

The locking signal can be initiated in various ways; a convenient method is to operate with the transmitting valve normally short-circuited by back contacts on the fault-detecting relays, the short-circuit being removed, and allowing the signal to be emitted, when the fault-detecting relays function. Signalling by carrier current is usually quicker than by direct current, and with carrier-current locking the protective gear will be quicker than with direct-current locking. Fig. 14 is a schematic diagram of the arrangement for one end of a section of power line, and Fig. 15 shows a typical arrangement for mounting the line trap and capacitor on a common insulator.

The fault-detecting relays are of the overcurrent type and, as already described, two sets are provided at each end of the line. The low-set overcurrent relays have two sets of circuit-opening contacts and one set of circuit-

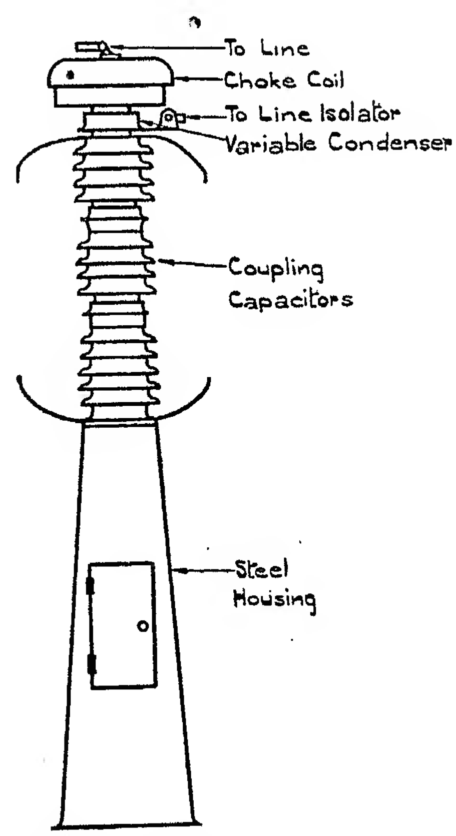


Fig. 15.—Arrangement for mounting carrier line trap and coupling capacitor on common insulator and pedestal.

closing contacts. One set of the former are connected in series and normally short-circuit the transmitting valve, whilst the other set, also connected in series, normally energize the restraint coils 5X of the directional relay and 6X of the signal-receiving relay. Normally the restraint coil maintains the directional relay in the position representing power flowing out of the feeder. The high-set overcurrent relays 1A, 2A, and 3A, have a single set of circuit-closing contacts connected in parallel and included in the trip-coil circuit of the circuit-breaker. This circuit is completed through the circuit-closing contacts of the

* See Bibliography, (4).

directional relay 5 and the circuit-opening contacts of the signal receiving relay 6. The directional relay 5 also has a circuit-opening contact which is connected in the circuit of the cathode of the transmitting valve and removes the carrier signal when fault power is flowing in the direction of the feeder. The signal-receiving relay is of the double-wound polarized type with restraining coil 6X and signal-receiving coil 6; it has three circuit-closing contacts and one circuit-opening contact. Relay 7 is the surge-guard relay which operates in the manner already described.

The supply for the valve anodes (which is usually of the order of 200 volts d.c.) can be taken from the station battery; if the voltage of the battery is too low the supply can be obtained from a small motor-generator fed from the battery and running continuously. If an a.c. generator is used its output must be rectified, a tapped transformer providing voltage adjustment and, in addition, a low-voltage supply for the valve filaments.

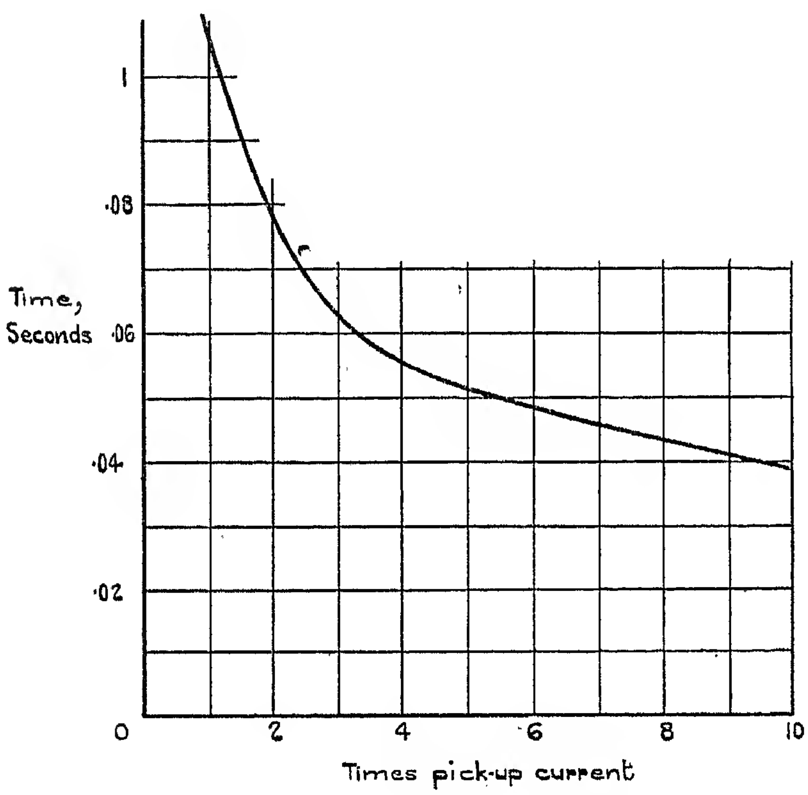


Fig. 16.—Typical time/current curve for lock-in protection.

When the feeder is carrying fault current, the low-set overcurrent relays 1, 2, or 3, pick up, initiate the carrier signal, and remove the restraint from the directional relays 5 and the signal-receiving relays 6. If the fault is on some other part of the network one of the directional relays stays in its normal position and maintains the carrier signal. If, however, the fault is on the feeder, both directional relays move into the tripping position and thus remove the carrier signal. The signal-receiving relays will then drop, prepare the tripping circuit and remove the short-circuit from the coils of the high-set overcurrent relays 1A, 2A, and 3A, which operate and trip both circuit-breakers.

The authors believe that the use of carrier-current signalling for protective purposes will, in the future, largely replace other forms of protection, particularly for overhead lines. Carrier-current relaying as at present developed offers practically the same advantages that are obtained by the use of pilot wires; moreover the relays are easily applied to the most complicated network and it is not necessary to make a detailed study of system short-circuit conditions, etc., when designing the protective gear.

(c) High-Speed Distance Relaying

If pilot wires or carrier currents cannot be employed it is usually possible to make use of some form of distance relaying and thus obtain high-speed tripping for faults over part of the feeder length. If the feeders terminate in a power transformer or reactor the high-speed distance relays can be set to cover the entire feeder length, but generally they can only be set to cover 75 % of the feeder, and discrimination for faults on the remainder will be by means of time delay. It is for this reason that distance relaying cannot be considered as the equal of pilot or

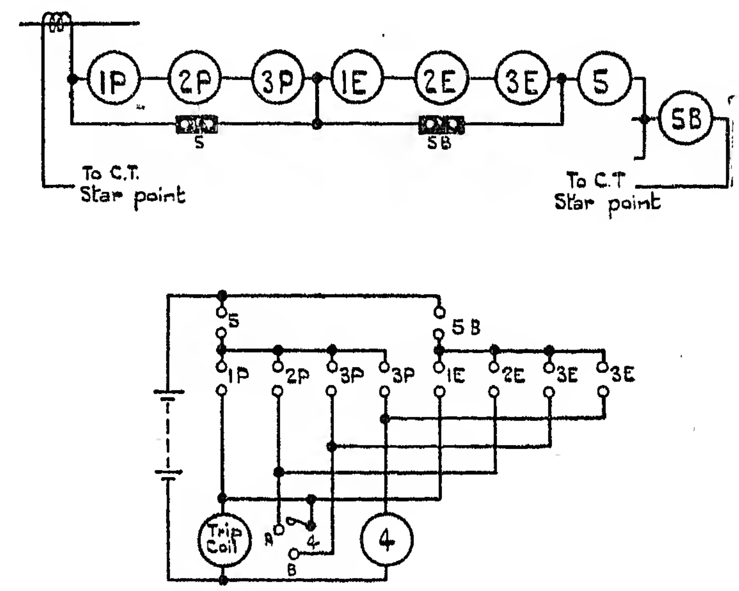


Fig. 17.—Schematic diagram (for one phase only) of high speed impedance protective system. (Current-coil connections only shown. Voltage-coil connections omitted for clarity.)

1P, 2P, 3P = 1st, 2nd and 3rd zone phase-fault impedance elements, respectively.
1E, 2E, 3E = ditto, earth-fault elements.
4 = Time-delay relay having contacts 4A and 4B.
5 = Phase-fault directional relay.
5B = Earth-fault directional relay.

carrier-current relaying, but it can be used successfully in many cases and in fact offers the only alternative where quick tripping is required.

It is not proposed to discuss the various kinds of distance relays which are available, but to describe the schemes based on the distance measurement by the impedance principle.

The distance-measuring relay is of the beam pattern, the current coil being energized directly from the line current transformer, while the voltage coil is energized through a rectifier from the voltage transformer. The rectifier is introduced for two reasons: (*a*) To minimize inaccuracy in measurement at different power factors due to the peak of the current wave varying in phase with respect to the peak of the voltage wave. (Such inaccuracy only arises when relays are of the high speed type in which the measurement of impedance is made in one cycle or less.) (*b*) To avoid the vibration which occurs on a.c. electromagnets and to allow of the introduction of a non-magnetic spacer between the armature and the

pole-faces. The iron circuit of the voltage element is made from nickel-iron alloy having high permeability and low hysteresis, which makes it possible to obtain high working

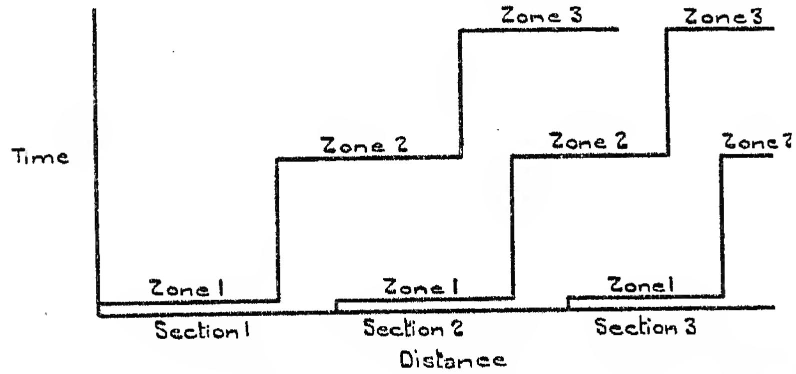
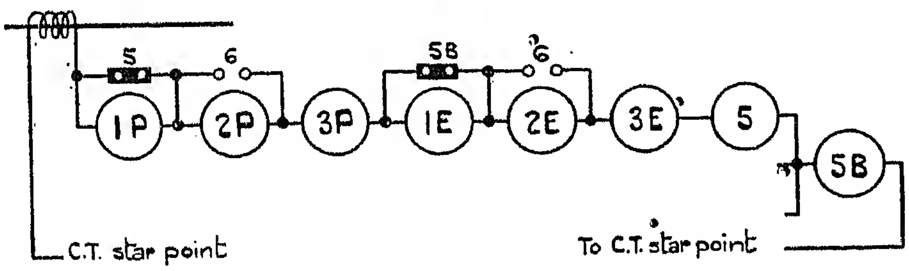


Fig. 18.—Time/distance characteristic for high-speed impedance protective system having time-stepped discrimination.

forces at low voltages without exceeding the thermal rating of the coil at normal voltage.

The directional relay is of the induction-disc type with a voltage-operated biasing element which holds the con-



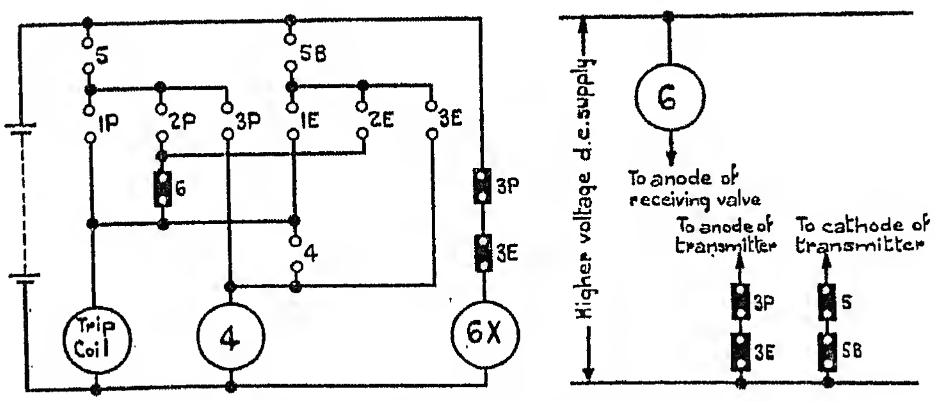


Fig. 19.—Schematic diagram (for one phase only) of high-speed impedance protective system with carrier-current locking on the second zone.

1P, 2P, 3P = 1st, 2nd and 3rd zone phase-fault impedance elements, respectively.
1E, 2E, 3E = ditto, earth-fault elements.
4 = Time-delay relay having contacts 4A and 4B.
5 = Phase-fault directional relay.
5B = Earth-fault directional relay.
6 = Carrier-receiving relay.
6X = D.c. restraint coil on relay 6.

tact in the open position during normal conditions irrespective of the direction of power flow, as already described. In the case of earth-fault relays responsive only to zero phase-sequence currents, the bias can be dispensed with as the control spring is sufficient to keep the contacts open.

A schematic diagram showing the relay connections for protecting one phase of a feeder by this method is shown in Fig. 17. Six impedance elements are used for each phase, three being connected to measure the impedance under phase-fault conditions and three under earth-fault conditions. One element of each set is adjusted to operate for faults over the first 75 % of the feeder length; the second element is set for a distance up to 50 % into the next section; whilst the third or back-up element covers a distance up to 25 % into the third section. The setting distances are termed " zones " in Fig. 18, which shows the time/distance characteristics for three feeders in series.

The time-delay relay used to give the stepped discrimination must be sufficiently accurate to measure small intervals of time. Two adjustable contacts give the separate time intervals between the zones, and the relay is energized from the tripping battery by a contact on the third zone impedance element.

The current coils of the impedance elements are normally short-circuited by back contacts on the directional relays 5 and 5B, and are thus prevented from operating unless the directional relay indicates that fault power is flowing away from the busbar.

A phase fault within the first zone will operate all three impedance elements, and the first zone element will trip the circuit breaker without delay through the contacts 5 and 1P in series. A fault within the second zone will not operate the first zone impedance element since the torque due to the voltage will exceed that due to the current, and the circuit-breaker will be tripped by the first contact of the time delay relay 4, through the contacts 5, 2P, and 4A, in series. A fault within the third zone will not operate the first or second zone elements, and the circuit-breaker will be tripped through the second contact on the time-delay relay through the contacts 5, 3P, and 4B, in series; the latter condition representing back-up protection.

(d) Distance Relaying with Carrier-Current Locking

The chief objection to the foregoing method is the unavoidable delay on zone 2, which may be of the order of 0·5 sec. This may be obviated by substituting the locking principle for the time discrimination used on this zone. The advantages of such a combination are that the distance relays will not operate during faults on a

distant part of the network, and that high-speed tripping is obtained over 100 % of the feeder length. Fig. 19 shows schematically a diagram of an arrangement embodying distance relays with carrier-current controlled locking.

The current coils of the first and second zone impedance elements are normally short-circuited by directional relay contacts 5 and carrier-receiving relay contacts 6 respectively (or similarly contacts 5B and 6 respectively for the earth-fault elements), and thus, similar to the arrangement in the previous scheme, operation of these elements is confined to conditions of fault power flowing in the correct direction for tripping.

With a phase fault in the first zone, tripping is effected through the contacts 5 and 1P in series, directly energizing the trip circuit. Faults in the last 25 % of the first line section, i.e. coming within the second zone, will cause the 2nd and 3rd zone impedance elements to operate; no carrier locking-signal will be received at either end of the first line section, and the carrier-receiving relay 6 will be de-energized. Hence in this case the trip circuit will be completed through the contacts 5, 2P, and 6, in series, giving tripping without the inclusion of any time delay.

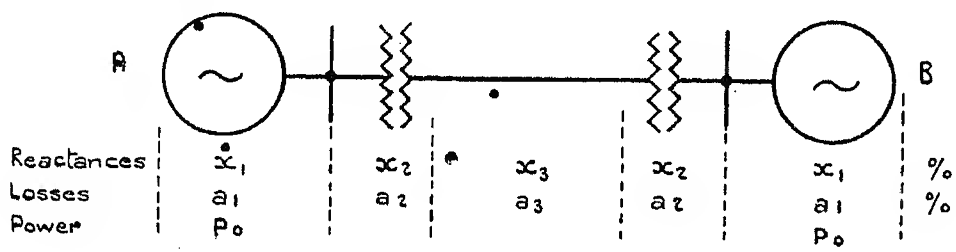


Fig. 20.—Typical system showing two generators interconnected through transformers and a transmission line.

For through faults occurring in the third zone, the carrier signal will maintain relay 6 in the energized position and thus lock-in the circuit-breaker. Back-up protection is provided by a time-delay relay operated by the third zone impedance element, and will trip the circuit-breaker through contacts 5, 3P, and 4, in series.

(5) CONCLUSION

The demand for high-speed protection arose because of the difficulty of maintaining stability during and following short-circuits on certain networks abroad. Conditions in this country are such that instability is seldom approached; nevertheless, operating engineers are anxious to avail themselves of recent improvements in circuit-breaker and relay technique in order to increase system reliability.

The type of short-circuit most likely to give rise to instability is one involving two or three phases and occurring close to a generating station. Primary considerations should therefore be given to nearby circuits, in particular those operating at generated voltage.

High-speed protection also provides a means of decreasing the interference with machine loads brought about by network faults. Further, a reduction in the damage to conductors or other apparatus is obtained, while there is less likelihood of a fault arc spreading to other circuits.

Finally, quicker relay operation has not been obtained at the expense of discriminative ability, which still remains the fundamental feature of any protective apparatus.

ACKNOWLEDGMENTS

The authors wish to express their thanks to the Metropolitan-Vickers Electrical Co., Ltd., for permission to publish the paper, and to their many colleagues for helpful criticism and advice. In particular they would acknowledge the assistance of Mr. R. M. A. Smith in the preparation of the paper, and also their indebtedness to the Automatic Telephone and Electric Co., Ltd., for permission to reproduce photographs of the carrier-current telephone and signalling apparatus.

BIBLIOGRAPHY

(1) W. D. Horsley: "The Stability Characteristics of Alternators and of Large Interconnected Systems," *Journal I.E.E.*, 1935, vol. 77, p. 577.
(2) R. D. Booth and O. G. C. Dahl: "Power System Stability," *General Electric Review*, 1930, vol. 33, p. 677, and 1931, vol. 34, p. 131.
(3) R. H. Park and E. H. Bancker: "System Stability as a Design Problem," *Transactions of the American I.E.E.*, 1929, vol. 48, p. 170.
(4) H. D. Braley and J. L. Harvey: "Out-of-Step Protection," *ibid.*, 1935, vol. 54, p. 189.
(5) W. C. Hahn and C. F. Wagner: "Standard Decrement Curves," *ibid.*, 1932, vol. 51, p. 353.
(6) T. W. Ross and M. Kaufmann: "The Protection of A.C. Generators," *Metropolitan Vickers Gazette*, 1929, vol. 11, pp. 212, 245, 262, 297.
(7) T. W. Ross and H. G. Bell: "The Protection of Three-Phase Transmission Lines and Feeders," *Journal I.E.E.*, 1930, vol. 68, p. 801.

APPENDIX 1

Method of Determination of Rotor Phase Displacements Used in Constructing Figs. 2 and 3

Consider the system shown in Fig. 20 wherein two 3-phase alternators are coupled together through two transformers and a transmission line.

Let the reactances and losses be as indicated in Fig. 20.

For a fault at, say, one end of the line the system reactance referred to or viewed from the point of fault is $(X_1 + X_2 + X_3)$ %, or similarly $(X_1 + 2X_2 + X_3)$ % for a fault on the "other" machine terminals. The losses in these cases will be $(a_1 + a_2 + a_3)$ % and $(a_1 + 2a_2 + a_3)$ %, respectively.

In determining the system reactance to any fault position due allowance must be included as necessary for the lower subtransient reactance of machines with damping windings, etc. Knowing the machine transient reactance, the subtransient reactance may be determined from the equation

$$X_t = 1 \cdot 4X_s + 2$$

where X_t is the transient reactance (saturated), and
X_s is the subtransient reactance (saturated).

Using standard short-circuit decrement curves* for synchronous machines, the fault current at any time after the incidence of the fault may be determined.

Let the losses $\Sigma(a)$ (above) be P_1

Then decelerating power $= P_1 - P_0$

where P_0 is the constant power input, since during the short periods under consideration it is assumed that the governor setting has not altered.

Then, equating energy losses,

$$(P_1 - P_0) \cdot (t_0 - t_1) = \tfrac{1}{2}I(\omega_0^2 - \omega_1^2)$$

where I = moment of inertia of the generator and turbine rotors, exciters, etc.,
ω_0 = initial (synchronous) angular velocity at time t_0, and
ω_1 = angular velocity at time t_1.

The angular displacement θ in the time $(t_0 - t_1)$ is then given by $\theta = \frac{1}{2}(\omega_0 - \omega_1) \cdot (t_0 - t_1)$

The calculations for times t_2, t_3, etc., giving the displacements θ_2, θ_3, etc., from which the curves may be drawn, are made in a similar way to the above.

APPENDIX 2

Synchronizing Power of an Interconnector

The synchronizing power of an interconnector may be defined as the amount of additional power which will flow through the line when the phase angle between the station voltages is displaced by a definite angle θ from the stable angle α.

Considering the vector diagram (Fig. 21):—

Let P_S = power in watts delivered by sending end.
P_R = power in watts delivered to receiving end.
α = stable phase angle between station voltages.
E_a = phase voltage at sending end.
E_b = phase voltage at receiving end.
X = reactance to neutral in ohms per conductor
R = resistance to neutral in ohms per conductor
Z = impedance to neutral in ohms per conductor
(including transformers and generators)
I = current in interconnector.
Cos ϕ_a = power factor at sending end.
Cos ϕ_b = power factor at receiving end.

Then $\qquad P_R = 3E_bI\cos\phi_b \quad . \quad . \quad . \quad . \quad (1)$

and $\qquad P_S = 3E_aI\cos\phi_a \quad . \quad . \quad . \quad . \quad (2)$

from which it may be shown that

$$P_R = \frac{3E_aE_b}{Z^2} \cdot \left[X\sin\alpha + R\cos\alpha - R \cdot \frac{E_b}{E_a}\right]. \quad (3)$$

and

$$P_S = \frac{3E_aE_b}{Z^2} \cdot \left[X\sin\alpha - R\cos\alpha + R \cdot \frac{E_b}{E_a}\right]. \quad (4)$$

If the phase angle α be increased to $(\alpha + \theta)$, then

$$P_R = \frac{3E_aE_b}{Z^2} \cdot \left[X\sin(\alpha+\theta) + R\cos(\alpha+\theta) - R \cdot \frac{E_b}{E_a}\right] \quad (5)$$

and

$$P_S = \frac{3E_aE_b}{Z^2} \cdot \left[X\sin(\alpha+\theta) - R\cos(\alpha+\theta) + R \cdot \frac{E_b}{E_a}\right] \quad (6)$$

The increase in P_S after deducting half the increase of line losses gives the synchronizing power available at the centre of the line, i.e.

$$W_s = \frac{3X}{Z^2} \cdot E_aE_b[\sin(\alpha + \theta) - \sin\alpha] \text{ watts}$$

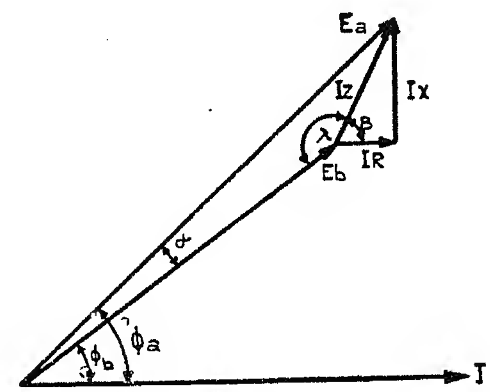


Fig. 21

From this it will be seen that W_s is zero when $X = 0$, and W_s is very small when X or Z is large. The optimum condition allowing the maximum synchronizing power to flow is when $R \doteq X$.

For the case of equally locally loaded machines when $\alpha = 0$,

$$W_s \simeq \frac{3X \cdot E_aE_b\theta}{Z^2}$$

for normal additional load increments.

APPENDIX 3

Effect of System Oscillations upon Relay Operation

System oscillation is defined as the oscillating interchange of power between synchronous machines, and is generally brought about by severe short-circuits.

For the purpose of investigation assume that

(1) The system is represented by Fig. 22.
(2) The generated voltages are equal and constant in magnitude.
(3) All parts of the system have the same ratio of resistance to reactance.

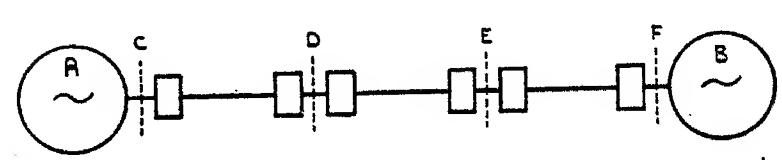


Fig. 22.—Single-phase diagram of three sections of transmission line connecting two generating sources A and B.

Since the type of oscillations involved are balanced 3-phase phenomena, it is only necessary to consider the current in one phase and its relation to line-to-neutral voltage as shown in Fig. 23. The difference voltage $V_A \ominus V_B$ causes current I to flow through the total impedance between the two generating sources A and B. As the angle θ increases from zero to a maximum and diminishes to zero again, the angle between the substation voltages and I, together with the magnitude of I, changes, although the angle ϕ remains constant. The relative

* See Bibliography, (5).

changes in the current, synchronizing power, and voltages, at the various substations for values of θ up to 90° are shown in Fig. 24.

The numerical relationship between θ and the various

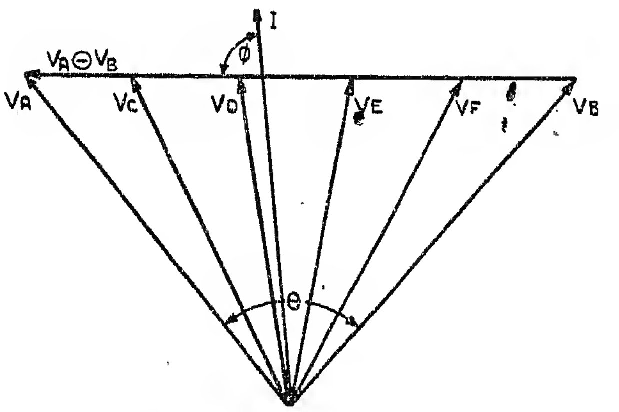


Fig. 23.—Vector diagram showing relation between line-to-neutral voltage and current of one phase at the various section points of Fig. 22, when the generated voltage of source A is θ° in advance of the corresponding voltage at source B.

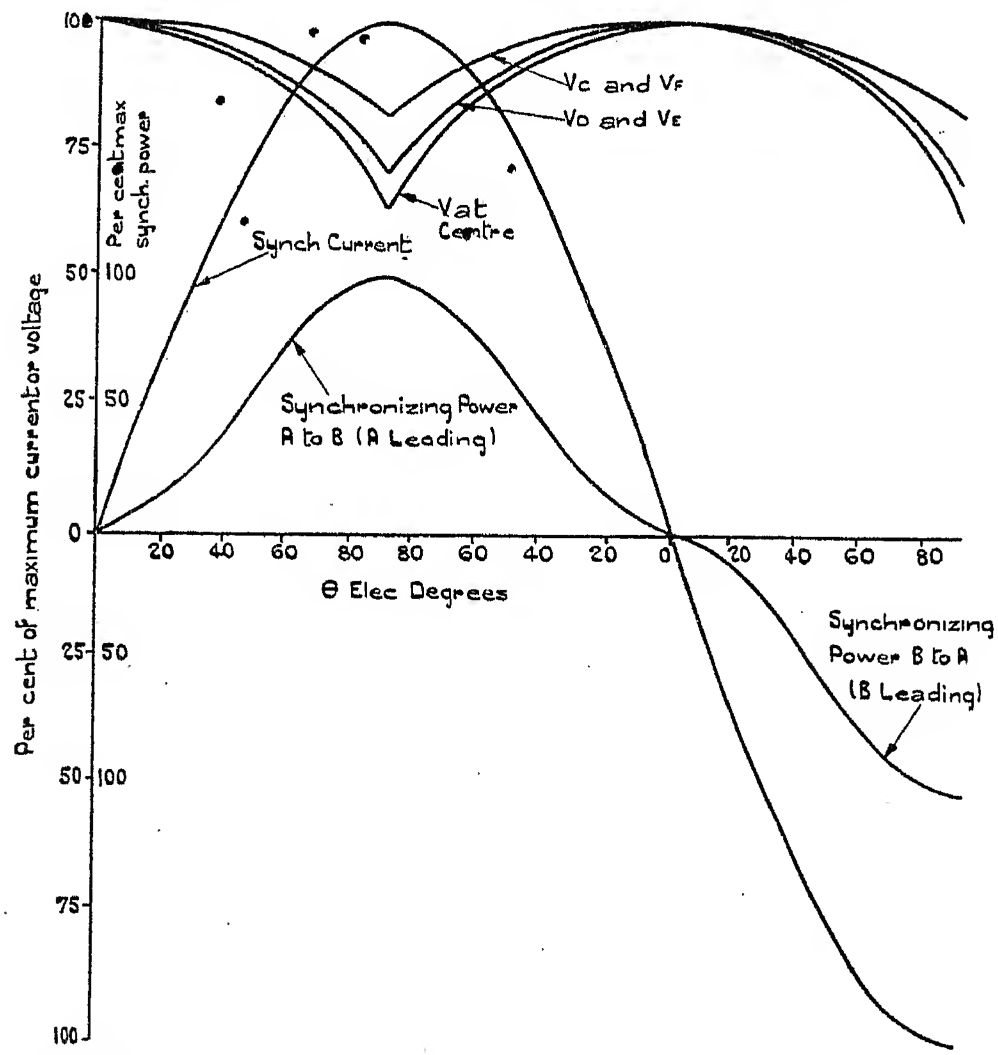


Fig. 24.—Curves showing relations between station voltages, current, and synchronizing power, for the system depicted in Figs. 22 and 23.

quantities affecting relay operation are given by the following equations, θ being measured anti-clockwise from V_B to V_A.

$$I = \frac{V_A \ominus V_B}{Z}$$

$$= 2V_A \, . \sin \tfrac{1}{2}\theta / Z \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$V = V_A \sqrt{\left[\frac{4a^2}{Z} \, . \sin^2 \tfrac{1}{2}\theta + \cos^2 \tfrac{1}{2}\theta\right]} \quad . \quad (2)$$

$$\alpha = \text{arc tan}\left[\frac{2a}{Z} \, . \tan \tfrac{1}{2}\theta\right] - (90 - \phi). \quad (3)$$

where V = voltage at intermediate points,
a = total line-to-neutral impedance from centre of line,
Z = total line-to-neutral impedance of the system, and
α = angle between V and I. When α is positive I is lagging behind V.

From these equations the current and voltage conditions for the relays at opposite ends of a section may be determined for maximum values of θ likely to be met with in the system being considered.

As far as directional relays are concerned, the overlapping of their contacts will be negligible for values of θ of the order mentioned, since I will be passing through zero as the direction of power changes. In practice, however, some allowance must be made for the fact that the system voltages may not be equal, in which case the power direction would change without I having passed through zero. Furthermore, there is the possibility of a complete loss of synchronism when the power would change direction with I at its maximum as θ passed through 180° displacement.

[The discussion on this paper will be found on page 243.]

DISCUSSION BEFORE THE TRANSMISSION SECTION, 16TH FEBRUARY, 1938

Mr. C. W. Marshall: The authors draw attention to the greater spread of system faults arising from interconnection, and there is no doubt that without discriminative protective gear large-scale interconnection would be impracticable. When this stage of development took place in Britain, in 1927, the development of protective gear was somewhat primitive, and even now protective-gear engineers have hardly reached the standards of efficiency which commercial requirements demand. We find that with the relatively low-speed protective gear existing at present we can clear about 86 % of all the faults without serious disturbance to the system, but something approaching 100 % is wanted by users of electricity. The only section on which we do get 100 % clearance is where we have balanced pilot-wire equipment. On the overhead lines where pilot wires were ruled out on the ground of cost, and distance protection was used, during last year there was only one case of quite incorrect operation, but in rather a large proportion more than the essential circuit-breakers operated, and even to obtain that standard of accuracy meticulous maintenance is required.

The low-speed induction-disc impedance relay, which is used for distance protection generally, is not an instrument of precision, and a great deal depends on the quality of the men who carry out field adjustment as to the degree of satisfaction which is obtained from such protection. I hope that the advent of modern high-speed beam-balance relays will make it possible to give something approaching 100 % correct operation, but I fail to see how the ideal is to be obtained other than by a reversion to the unit system, probably employing interlocked methods operated from the carrier-current system in the case of very high-voltage lines and inexpensive pilot wires in case of low-voltage lines.

I would touch briefly on the nature of the troubles with protective gear which we experience. It frequently takes periods as long as 1 sec. to get entirely clear of faults, and in the meantime rotary convertors are tripped off the busbars, usually on the d.c. side. The authors show how, by the use of time-lag relays, such troubles may be avoided, and I can testify to the success of the means which they have devised for this purpose; but such artifices should not be necessary, and the real remedy lies in clearing faults in a very few cycles instead of in about 50 cycles, as is customary at the present time.

Induction relays appear to work satisfactorily as directional relays, but are they not in fact inherently less reliable than beam-balance relays for a given volt-ampere consumption? I should like to have particulars of the performances of such relays of both types.

In the Appendices the authors show that at long last protective-gear design is emerging from the rule-of-thumb stage, but the Appendices have been so curtailed that it is not possible to obtain from them all the information which is desirable. For example, in regard to Appendix 1, I should like to know how the authors define the transient reactance (saturated) and the sub-transient reactance (saturated), and what units they use in the expression for the sub-transient reactance. Again, it would be useful to know what figures they have taken for the moments of inertia of typical machines, e.g. 30-MW 3 000-r.p.m. and 50-MW 1 500-r.p.m. turbo-alternators and 1·5-MW rotary convertors.

Mr. F. C. Winfield: The authors might with advantage have laid emphasis on the reduction in plant damage which we hope to achieve by high-speed switching and relaying. Examples in a.c. practice are naturally not yet available, but we have come across a 3 000-volt d.c. traction system abroad in which intolerable interruptions of supply took place at every lightning season owing to the failure of track insulators. The insulation of the track conductors was of quite high quality, but damage to these occurred every time there was a lightning stroke, and occasionally conductors were burned through and brought down. The trouble was entirely cured by the introduction of high-speed d.c. circuit-breakers.

In this country we depend very much on overhead lines for our supply of power, and the chief bugbear of overhead lines is lightning. It is a common experience, at almost any voltage from 20 kV upwards, that something approaching 50 % of lightning faults produce damage which requires insulation replacement or similar attention. If we had high-speed switching and relaying we might reasonably hope that that figure would fall to about 10 %, and the reliability of our lines would much more nearly approach the cable factor.

On low-voltage lines, experience shows that auto-reclosing switchgear on single-ended feeders will almost overcome the lightning trouble, or at least reduce it to reasonable dimensions. With high-speed switching in addition we could expect it to approach the ideal very nearly. I have no doubt that similar remarks would apply to high-voltage lines, particularly those with high-speed circuit-breakers; but unfortunately in high-voltage working we very rarely have single-ended lines—the lines are usually parts of ring mains or parallel circuits, and questions of synchronism come in. We cannot reclose a line, automatically or otherwise, without checking synchronism, and the idea of high-speed switches immediately suggests the possibility of introducing high-speed reclosing automatic circuit-breakers which would operate so fast that we could keep the synchronism and the stability factor discussed in the paper. This requires the relays to operate, the circuit-breaker to trip, and time to be allowed for the ionized air to be dissipated and then the circuit-breaker to be reclosed. All this must take place in a very short period of time, and I should like to know whether the authors consider there is any likelihood of it being achieved. Have they, for example, any idea of what time they ought to allow for the dissipation of ionized air following the flashover of an insulator? How long is required to reclose a high-speed circuit-breaker? They mention a figure of 0·25 sec. for plant remaining in synchronism: this is a very short time, and it only applies to the 3-phase fault condition, which is very rare. Do they consider it possible to restrict auto-reclosing to the single-phase fault condition?

I suggest that there is some slackness in speaking about the times of circuit-breakers and relays. The important time of operation of a circuit-breaker is its worst time, not its best, and a similar remark applies to a relay. In

fixing the discriminating intervals of protective systems we have to add the circuit-breaker's worst time and the protective relay's worst time to obtain the true time-interval, and finally we ought to add a margin to allow for errors.

I do not agree with the authors when they say that we can deal with motor overloads by thermal methods. We have developed a laboratory instrument to do this, but I do not think it is true that there exists in commercial practice a thermal relay which, in conjunction with any system of protection the authors liked to select, would deal with all motor faults. I have in mind particularly direct-starting motors, but any local system fault condition produces a direct starting condition, or something analogous to it, in the starting circuit. There is only one method of attacking the problem, and that is a direct-measuring temperature device which would attempt to measure the temperature of the insulation on the motor itself. If such a device could be produced commercially, then I would agree with the authors.

On page 232 the authors say "Asymmetrical current conditions during the initial stages of a fault do not appear to have any deleterious effect upon the operation of induction-type directional relays." They also say that we can now use relays having operating times approaching a half-cycle. This is a very bold statement; can the authors support it academically? Is it capable of argument?

I would add a lament about the general tendency of protective gear to become too complicated. The authors' diagrams show protective systems embodying from 4 to 10 relays per circuit-end, and I am sure that we are approaching the position where the protective gear will give more trouble than the circuits which it protects.

Mr. C. H. Flurscheim: The curves calculated by the authors for the permissible time to clear a fault when this is fed by two stations, without bringing about loss of synchronism, are of particular interest. There are no doubt many cases when 0·5 to 1 sec. may be a safe clearing time, but instances may arise when very much shorter times are necessary.

One of the most promising tools now becoming available to aid in improving continuity of supply on overhead lines is the rapid-reclosing circuit-breaker, and the cases calculated by the authors do not apply to this type of service. Referring to Fig. 1 of the paper, if the fault is on the tie connector between the stations instead of on a feeder fed by both stations from No. 1 busbar, while the fault persists the machine may diverge along a curve intermediate between A and B of Fig. 2. If the majority of the load has been supplied by No. 1 busbar prior to the occurrence of the short-circuit, once the tie-connector circuit-breakers have cleared No. 1 generator may be left with a considerable overload and will decelerate along curve A or even faster, depending upon the percentage of the total load and consequent steam conditions previously existing in No. 1 station. No. 2 generator, however, may have had full steam and full load, but is now left with no load and will accelerate along an equally steep curve. The divergence between the machines could therefore be at the rate of 100° in 0·1 sec. Consequently, if it is desired to re-establish the connector, the tie breakers have not only to clear the circuit as fast as possible in order to reduce divergence while the fault exists, but also to reclose within a further period which, under unfavourable circumstances, might be of the order of a few cycles.

This represents the worst case, inasmuch as the British grid, for instance, usually provides for an alternative synchronizing path round a ring-main system, but this path is often long and therefore of relatively lower synchronizing power.

It seems to me, therefore, that the remedy for air-flashover faults between stations rests in using high-speed protection, such as the 1- to 3-cycle types described by the authors, together with the fastest opening and reclosing breakers that the economics of each case may justify.

Impulse-type breakers are available with operating times of 3 cycles. These breakers, arcing for one cycle, require their main contacts to move only a few inches to ensure interruption at all current values, and the contacts may therefore be safely reclosed before the breaker is fully open. Consequently the mechanical reclosing time may be no longer a limitation. The real limiting factor becomes the de-ionization time necessary to restore the electric strength of the arc path at the fault, once the arc current has ceased to flow. This time in its turn has been demonstrated to be a function of the prior arcing time, a further argument for reducing the total clearance time of relay and breaker.

A further possibility which has been suggested with reclosing breakers to aid in reducing disturbance is single-phase switching. This also can be provided on the impulse breaker, and I should like to ask the authors whether they consider that the reduced shock on clearing a single-phase fault due to retaining a 2-phase tie would justify the increased relaying complications.

Mr. T. B. D. Terroni: The system of carrier protection described in the paper is based on the application of carrier signals to the line to lock out the trip circuit at each end of the protected section of line until the directional relays have been operated to allow the circuits to trip. A rather interesting feature of this arrangement is that the fault relays are built up in two sections, a low-fault-setting relay and a heavy-fault-setting relay, so that at the instant of a fault of any description and in any position, whether inside the protected section or outside it, or even in the event of a line surge, the carrier is immediately applied to the line and effectively prevents any possibility of tripping of the circuit-breakers. In addition to that feature, there is a voltage restraint which is placed on the directional relay so as to hold it in the no-trip direction. This voltage restraint is supplied from the tripping battery, and the combination of the low-fault-setting relay and the restraint on the directional relay seems to me to preclude the possibility of faulty tripping due to the racing of the protective relays at the two ends of the line.

The essential feature of the carrier system, which I do not think the authors emphasize sufficiently, is the fact that the operation is dependent upon the cessation of the carrier. This necessarily implies that even in the event of a short-circuit between the two lines upon which carrier has been applied, or the disconnection of these two lines by faults which in themselves would prevent

the reception of the carrier at the far end, the equipment will give satisfactory operation.

Another point which is not clear from the paper is that if any attempt were made to design a carrier protective system whereby the initiation of a carrier on the line caused closing of the tripping circuit, it would be seen at once that the system was not feasible owing to the interruption in the transmission of the carrier by possible short-circuit faults on the lines, or line disconnections.

An alternative system of protection, which I think is used in Germany, is based on the same idea as that described in the paper, but instead of applying the carrier in the way described it maintains the carrier on the line all the time, tripping being effected by removing the carrier, as in the system described by the authors. One of the advantages claimed for that system is the continuous supervision which is provided for the valve and carrier equipment generally, and in this connection I should be interested to have the views of the authors on the efficiency and frequency of supervisory testing of their carrier equipment.

The authors' system of carrier protection to which I have referred is such that interference produced by storm or surge conditions on the line cannot give rise to faulty tripping of the breakers, owing to the fact that the relay which closes the tripping circuit on the release of the carrier is normally held operated from an auxiliary winding energized by the tripping battery. The only possibility of faulty operation which can in fact arise is where interference appears on the line at the instant when the carrier current is removed and tripping is required, the interference condition maintaining the carrier receiver in operation and thereby preventing tripping for the duration of the interference condition.

Mr. A. J. Gibbons: When preparing the paper the authors have had largely in mind the protection of overhead lines of considerable length. They make references to other classes of apparatus, however, to which I should like to devote some time.

So far as urban cable networks are concerned, there is no doubt that the more we are connected up with external overhead lines the more we are subjected to disturbances. The speed of tripping of high-voltage lines is of great importance to the engineers responsible for operating urban networks. Most high-voltage cables and transformers are equipped with fast-acting protective gear, but disturbances are caused when faulty overhead lines are clearing with considerable time-delays. Any such fault is liable to cause trouble to power-station auxiliary motors, which are frequently of the high-voltage direct-starting type. The authors rather recommend negative phase-sequence gear for this purpose; I have made one or two tentative inquiries about this and have ascertained that it is subject to trouble in connection with the question of volt-ampere burden. It is possible to improve matters, in spite of what the authors say, by means of time-delay over-current relays which are cut out during starting, provided some measure of protection is given by an earth-leakage relay. No-volt relays should be set as no-volt relays, not as under-voltage relays.

The authors put forward two forms of gear for overhead-line protection, the high-speed impedance and the high-speed interlock types. I think that the carrier-current interlocking system is fundamentally sounder than time-distance gear. However fast the latter is made, it has a section at each end which requires a discriminative time-lag, so that, so far as I can see, high-speed clearance of faults can be obtained on only 50 % of the line. The authors' high-speed gear has probably cut down the time-delays on the end sections, but it seems to me that the performance of that system must be worse than that of the carrier-current system. I should like to know what is the total volt-ampere burden of some of the assemblages of relays shown by the authors. Fig. 19, for instance, shows eight relays on one current transformer.

The authors put forward proposals for improved speed of operation of various differential protection gears; I am a little doubtful about their suggestion for the use of bias. This has been advocated from time to time for a great many purposes—at one time it was put forward as a means of reducing the cost of current transformers, but without success.

In any protective-gear equipment the current-transformer performance, the relay performance, and the circuit-breaker performance, are all of vital importance, and we ought not to concentrate on one aspect to the exclusion of the others. I am rather doubtful whether the authors' proposals for high-speed differential protection using biased relays are going to provide faster protection than the unbiased schemes which are successfully employed at the moment. It would have been very instructive if they had been able to show oscillograms of the complete performance of some of the equipments referred to, including the transients in the relay circuits at the moment of incidence of a fault; and if they had been able to give the operating times of the schemes under internal-fault conditions.

Mr. J. G. Wellings: The authors infer that transient unbalance between current transformers is the main cause of instability in schemes of high-speed differential protection, and that the best means of overcoming such troubles is to incorporate electrical bias in the relays. While this may be one way of attaining the end in view, I would point out that amongst current-transformer designers of repute there is knowledge of how transient as well as sustained unbalance may be eliminated at the outset, and the adoption of such means is an alternative method of avoiding the instability referred to.

The time-constant of the current transformers undoubtedly plays a large part in this matter, and, by proper attention to the copper circuit as well as the iron circuit, differential schemes of protection may be rendered perfectly stable on through faults of any nature, simply by proper design of the transformers alone. By the same means, excellent sensitivity for faults within the protective zone may be obtained, even with the use of bar-primary transformers.

The authors feel that variation in the normal characterestics of current transformers is unavoidable; I do not share that view, unless of course the transformers are subjected to excessive secondary burdens. The provision of bias always increases the burden on the transformers, and care should be taken, in adopting such means, that the increased burden does not defeat the object in view. Provided this is suitably taken care of,

the scheme suggested by the authors appears to be good.

Referring to Fig. 7, I should like to ask the authors whether the auxiliary transformer (C) is of the air-gap or the solid-core type. The scheme presumably is essentially an opposed-voltage scheme, so that this transformer operates normally under open-circuit conditions. If so, all the other current transformers operate under open-circuit conditions also, and may cause undue burden to be thrown back on to the main current-transformer (A).

Dr. P. F. Stritzl: In the first part of the paper the authors deal with stability problems, and in the later sections they show how tripping of the healthy section can be prevented by suitable relays, biasing devices, and other means. The only lines to be tripped in the event of instability are then one or more ties between power stations. There are certainly cases where immediate tripping is necessary, but there will be many other cases where it may be sufficient to trip one of several ties existing between two power stations. From Fig. 2 it will be seen that in many cases the subsequent increase of the impedance will lead to the maintenance of stability.

On page 229, the use of exciters is advocated in order to improve the system regulation and to enable greater changes of load to be dealt with. It would be interesting to learn whether the authors have had any experience of the application of grid control in the exciter circuits for the same purpose. I think grid control in exciter circuits will have a wide field of application in the future.

Other speakers have already referred to the importance of automatic reclosing devices, especially those of the high-speed type; these devices introduce a further complication into the system, which will already be complicated enough if all the recommendations of the authors have been adopted. Certainly if they are all used a considerable degree of reliability can be obtained, but are many authorities economically in a position to make use of these complicated and expensive relay schemes? Mr. E. M. Hunter has published a curve showing the relative effectiveness of several different methods of improving service continuity.* This interesting comparison shows that by far the most economical means of avoiding the majority of outages is a device which has a higher operating speed than any of the schemes put forward by the authors, namely the Petersen coil. In my opinion this device should not be omitted from an enumeration of high-speed protective gear. If earth faults are practically eliminated by installing Petersen coils, a good deal of the dangers to system stability are removed; but also the remainder of the protective gear then becomes very much simpler and economically applicable to systems of medium or small size. On page 239, for instance, the authors point out that with impedance protection 6 separate relays are necessary at each feeder end. If earth faults are eliminated, this number will be reduced to 2. Continental practice shows that this reduction of the number of relays, coupled with their simplification, leads to their much wider application. Many of the valuable schemes advocated by the authors would also find much more application in this country if the number of faults and the number of types of fault were reduced by employing Petersen coils.

* *General Electric Review*, 1936, vol. 39, p. 590.

Mr. C. F. Mares: At the end of Section (3) the authors mention a feature by which they obtain a backward torque on the disc from the voltage coil. This seems to me to be a very good feature, especially for use on systems having long lines of high capacitance, and I cannot follow why they do not use it on lock-in systems of pilot protection, rather than d.c. restraint.

Fig. 6 shows a somewhat modernized version of a rather faster type of relay than the Translay. I should be interested to know whether increasing the number of ampere-turns on the relay has caused an increase in the burden which it imposes on the current transformers. It seems to me that if we force the relays in this way the bias will have to be correspondingly increased, and so we seem to have a vicious circle.

There is one other feature in connection with the lock-in scheme (Fig. 13) to which I should like to refer. The scheme involves a large number of normally-closed contacts, which play an important part in the correct functioning of the gear. I should be interested to know what steps the authors take to ensure that these are prevented from making bad contact in the course of time in consequence of oxidation or other causes. It has been my experience that unless considerable contact pressures are used trouble of this sort will be encountered. It seems to me that the contacts of relay No. 6 in Fig. 13 will have to be very efficient, because they are short-circuiting low-impedance current coils. If they fail to do this the whole sequential operation of the scheme is defeated, and it becomes a race between relay No. 9 (the lock-out relay) and the closing of directional relay No. 5.

Dr. W. Wilson: The authors' preference for instantaneous protective schemes I consider to be entirely sound. It is true that this country has not the same long-distance transmissions as, for example, the U.S.A., and therefore the same extreme conditions are not encountered; nevertheless, the advantages of instantaneous working are so marked that the types of scheme labelled (*a*) and (*b*) in Section (4) of the paper should always be preferred.

Protective schemes may be divided into three groups as regards pilot facilities. First, when ordinary pilots are available, there is no question that Type (*a*) should be used, whatever the length of line. I recently had occasion to test a scheme of this class with pilot resistances up to 3 000 ohms, and the results were perfectly satisfactory.

Secondly, there are cases where ordinary pilots are not available, but those of the telephone type can be obtained. If there is no other alternative, I agree with the authors that a lock-in method [Type (*b*)] should be employed; but I should prefer not to do so. In the first place, the protection afforded by (*b*) schemes is decidedly inferior to that of (*a*) schemes; and in the second, telephone pilots have definite drawbacks. For instance, in those districts where they may be required for protective purposes, they are generally overhead, and therefore at least as likely to break down as the transmission line. I should instead prefer to use one of the methods to be advocated for my third group.

This includes those cases where there are no pilots at all, and then I should favour one of two alternatives. If the line is overhead, it is frequently possible to run an

earth-core pilot, i.e. an earth cable containing four insulated copper cores. These cables cost little more than the plain earth cable, and provide perfectly for balanced protection of Type (*a*), and for telephony as well. But if this is not practicable, then I join with the authors in recommending a carrier-current channel, together with a Type (*b*) scheme. Such schemes were developed in this country by more than one firm as long as 5 or 6 years ago, but in my opinion have not been used as much as they deserve.

With regard to those cases where ordinary pilots are available, I agree that a biased scheme should be used. Mr. Gibbons seems to think that a bias is a device which is fixed to a relay. It is nothing of the kind; but is merely a method of designing the relay, or the circuit itself, so that the fault-setting is automatically a floating one, being low during normal-load conditions and high for through short-circuits. By means of it stability and sensitivity are both secured at the same time; and the stability ratio literally becomes infinity.

Of the protective schemes described in the paper, I prefer that shown in Fig. 7, on account of its simplicity; but I should like to see the summation transformer omitted and instead the current-transformer ratio of the three phases varied so as to produce a difference current directly. I should also like to see the operating and restraining coils interchanged, so that capacitance currents would flow in the latter and restrain instead of operating the relay. This modification would obviate the necessity for condenser E. I have had considerable experience with a scheme designed on that principle, and it is entirely stable, being particularly immune from the effects of surges in the line or pilots.

The authors specify a beam relay. This type of relay has many advantages, but one disadvantage from which it is apt to suffer is important if it is desired to use very fine settings, such as 5 %. During a short-circuit there may be some vibration on the switchboard and this may cause the beam to wobble a little; under these conditions the plunger on the operating side descends slightly, and the pull will momentarily increase and may be enough to bring down the beam. A Ferraris disc relay is of advantage if it is desired to use a fine setting.

Messrs. T. W. Ross and **C. Ryder** (*in reply*): Mr. Marshall's remarks are very valuable, since they represent the views of one of the largest users of protective gear in this country. Protective gear, unlike most other engineering products, depends so largely upon operating conditions for its success that the designers must co-operate with the operating engineers if the best results are to be obtained. We agree that prior to the advent of the grid the necessity to develop protective schemes applicable to overhead lines had not arisen in this country; schemes suitable for cable networks were further advanced here than elsewhere and it is now of interest to note that such schemes have proved 100 % reliable. This is the ideal for which all protective-gear engineers are striving and, in spite of the many difficulties to be overcome, due largely to economic considerations which lead to unfavourable system and switchgear arrangements, a very high degree of proficiency has been reached. A statement that 86 % of all the faults are cleared without serious disturbance to the system does not indicate how many relays, etc., had to function correctly in order to obtain that result; such a comparison would show a very high percentage of efficiency and would also indicate what the result would have been without discriminative protection.

So far as induction versus beam relays for directional purposes are concerned, it is somewhat difficult to make a direct comparison on a volt-ampere consumption basis. The reliability of the induction relay has been proved over many years and its wattmeter characteristic considerably simplifies its application. With regard to the beam relay, the movement itself is well known; its application as a directional device will depend upon whether limitations in its characteristics restrict its use or otherwise, rather than upon considerations of its reliability. We find, however, that many conditions arise in practice which make it advisable to use directional relays which operate as true wattmeters.

References quoted in the Bibliography will provide the information required regarding machine reactance. Machines of the sizes quoted were not used in our calculations, but the moment of inertia of a typical 37 000-kW, 3 000-r.p.m. machine may be taken as 45 tons-ft^2 (alternator rotor and turbo-runner). The moment of inertia of a typical 1 500-kW rotary convertor is 13 tons-ft^2.

High-speed auto-reclosing circuit-breakers are now being advocated by certain engineers as a means of maintaining synchronism following transient short-circuits, and we believe that these will prove very useful provided certain precautions are taken in their application. Mr. Winfield and Mr. Flurscheim suggest that single-phase switching might be considered for this purpose, and it would appear to be feasible to develop along such lines. It would be necessary, however, to arrange matters so that if after the first reclosure the fault still persists all three phases would trip and remain open.

Single-phase switching would, of course, avoid the complete severance of the faulty circuit and would thus assist in maintaining stability of the synchronous plant. It is doubtful whether high-speed auto-reclosing can be successfully employed in cases where complete severance of the tie between generating stations might occur, since, following very severe fault conditions, it may be impossible to regain synchronism. The circuit-breakers can be made to trip and reclose in, say, 0·24 sec., but it is not definite that the ionized air around the fault will be dissipated by this time; tests carried out in America, however, show that the air was clear in about 0·05 to 0·24 sec.

The section of the paper dealing with load stability was introduced to show that, in addition to high-speed network protection, some consideration must be given to the protection of the load machines if they are to remain in service following a network fault. In the first place some protection is required for dealing with short-circuits on the machine windings, and it is doubtful whether this can also be designed adequately to cover damage due to overloading, so that some other means must be used to take care of the latter condition. Thermally operated tripping devices are the most common, but we agree with Mr. Winfield that they do not always afford sufficient protection against overloading.

The subject of speed of operation of directional relays is very interesting and can be treated academically. So

far as our investigations have gone they show that the transient power factor condition during asymmetry assists the induction relay in its operation, even on circuits giving practically zero power factor (lagging). Numerous tests on circuits producing asymmetry substantiate this and there does not seem to be any reason for imposing a deliberate delay in their operation.

Mr. Terroni's remarks concerning the periodic checking of carrier-current apparatus are of importance. The usual method of supervision of the integrity of the carrier-current generating and receiving gear involves the initiation of a carrier signal at one end of the line section and to check that it is satisfactorily received at the other end. By transmitting a signal thus from each end in turn and receiving at the other all the carrier gear is effectively routined; it is considered that to carry this out once per shift is quite adequate.

Several speakers raise the question of the burden imposed on current transformers by relays, and the effect of this on the correct functioning of the protective equipment. The point is a very important one, since in most cases the gear has to maintain its stability up to very many times full rating. There is a tendency for engineers to judge current transformers for protective gear on the basis of their accuracy up to full rating, quite overlooking that it is the performance at the maximum short-circuit-current which is the important feature. All the protective schemes described in the paper include relays which are designed to operate from current-transformers of reasonable design, provided that minimum fault-current-settings are not too far below normal full-load current. For instance, the negative phase-sequence relays suggested for the protection of motors and mentioned by Mr. Gibbons require less than 5 volt-amperes at operating current, and the total burden per phase imposed by the relays as shown in Fig. 19 is approximately 20 VA at operating current.

The use of electrical bias for improving the stability of differential protective gear during through-fault conditions has proved highly satisfactory in service and is perhaps the only way to avoid the use of specially designed current transformers which will balance under the many conditions which arise in practice. We agree with Mr. Wellings that current transformers can probably be designed to suit most conditions when these are known, but in many cases the exact conditions are not known, and moreover they may change from time to time. In our opinion it is better, therefore, to use relays with suitable electrical bias and ordinary current transformers. It must also be appreciated that such an arrangement is much more flexible and allows the purchaser more freedom in arranging his switchgear and system layouts.

We can assure Mr. Gibbons that electrical bias will not affect the speed of the protective gear, and Mr. Wellings that the schemes shown in Figs. 6 and 7 are satisfactory as regards stability and sensitivity.

Mr. Mares asks what steps are taken to ensure that normally-closed contacts are effective, and suggests that trouble may arise unless considerable contact pressures are used. We find that the only precaution necessary is to design the current transformers for low secondary currents and so increase the impedance of the circuit which includes normally closed contacts. The duty on the latter is thus decreased and the contact resistance forms a negligible part of the circuit.

We agree with Dr. Stritzl that the Petersen coil can be very effective in clearing earth faults, and by preventing the spread of the fault-arc to other phases it will be effective in maintaining system stability. As, however, instability between synchronous plant is seldom brought about by faults to earth, we did not consider it necessary to include these coils in our description of high-speed protective gear. We have no experience in the application of thermionic devices to the control of exciters; we do not consider that such devices are necessary, since the major part of the delay is due to the magnetic circuit and not to the regulating devices. Dr. Stritzl also advocates a reduction in the number of distance relays by the use of phase-sequence networks, but our experience is that such schemes are not satisfactory, particularly where high-speed relays are involved.

Dr. Wilson and Mr. Wellings have raised questions regarding the differential protective scheme shown in Fig. 7. We prefer as far as possible to develop protective schemes which can be operated from standard current transformers, and for this reason we introduce the summation current transformer. The auxiliary transformer has an air-gap, the burden on the main current-transformers being largely governed by the length and cross-sections of the pilot wires.

AN OBJECTIVE NOISE-METER FOR THE MEASUREMENT OF MODERATE AND LOUD, STEADY AND IMPULSIVE NOISES

By A. H. DAVIS, D.Sc.

[From the National Physical Laboratory.]

[*Paper first received* 19*th December*, 1936, *and in final form* 31*st May*, 1937; *read before the* METER AND INSTRUMENT SECTION 4*th February*, 1938.]

SUMMARY

The present paper relates to an instrument of the microphone-amplifier-meter type, which has been adjusted for measuring the equivalent loudness of noise. Many noise-meters on these lines are available commercially, but the author has not met with any (other than those based on designs supplied to firms by the National Physical Laboratory) which give results even approximately correct for a series of impulsive sounds. The essential feature of the work now described has been the adjustment of the circuits of the meter so that it gives correct results for intermittent and impulsive noises, as well as for continuous tones. The paper describes the principles upon which an empirical adjustment was made, and produces evidence that the meter gives results in excellent agreement with average assessments, by the standard aural technique, of the equivalent loudness of a variety of moderate and loud noises. It is commented that meters which pass a certain specification for sound-level meters which has been tentatively proposed recently may give results for impulsive sounds very much below the true values of their equivalent loudness.

An important point revealed incidentally was that inconsistencies arise in aural measurements when the loudness of a noise is compared with that of a reference tone heard simultaneously. The difficulties are resolved by adopting a technique in which the noise and the reference tone are heard alternately.

INTRODUCTION

The meter actually employed in the work is portable and intended for several types of acoustical measurement, one of them being the objective measurement of the equivalent loudness of noise. An early form, not then finally adjusted for intermittent sounds, was employed by the author in 1934 in the demonstrations made by the British Association Committee on the Reduction of Noise, when various silenced and unsilenced motor-cycles were compared for loudness on a public road, and when, as a result of a critical survey of published material,* it was concluded that suitable objective meters could *compare* the loudness of a noise-producing source with that of a standard of the same kind agreed to be the maximum acceptable under a regulation.

Since that time considerable attention has been paid to ensuring that the meter will *measure* the equivalent loudness of impulsive sounds (such as the noises of the exhausts of motor and aircraft engines) as well as more continuous sounds, when the noises are at least as loud as ordinary conversation. Some alterations were made to this end. In its present form the instrument has been used for nearly 2 years for various noise measurements, including those which the Laboratory has made on vehicle noise for the Ministry of Transport's Departmental Committee on "Noise in the Operation of Mechanically Propelled Vehicles."*

DESCRIPTION OF THE INSTRUMENT

The circuit arrangements are given in Fig. 1, so far as they are relevant to the present paper. The instrument consists essentially of a condenser microphone, which has remained constant within 1 decibel for some years, a portable amplifier incorporating an output meter, various correcting circuits appropriate to the various uses of the instrument, and dial potentiometers by which the sensitivity of the apparatus can be varied in steps of 1 decibel. The dials are adjusted in precise use until a standard deflection is obtained on the indicating meter; for approximate work the scale of the meter may be calibrated and read in association with the dials. As designed, the meter is sensitive enough to measure sounds down to about 40 phons in loudness; probably, with some rearrangement, two valves could be omitted if the meter were limited in use to sounds about 80 phons in equivalent loudness. Supply batteries (dry cells) are accommodated in a second case. A multi-range voltmeter with selector switch is provided for checking the supply voltages.†

The amplifier is of resistance-capacitance type, with "decoupling" resistances and condensers for reducing the unwanted coupling between successive stages which arises from the use of a common high-tension battery. The decoupling condenser of the last valve, the rectifier, is in two parts, one connected to each terminal of the valve filament,‡ to reduce coupling due to a common filament-battery. The indicator is a quick-moving milliammeter in association with the rectifying valve. The amplifier itself has practically uniform sensitivity over the audible frequency range. When it is used with a condenser microphone for measurements of sound and noise, resonances in the microphone are compensated by putting an appropriate series-tuned circuit in parallel with the anode resistance M. In order that the instrument may be used for measuring the equivalent loudness of pure tones of various frequencies a switch modifies the circuit at L and H in the manner necessary to make the frequency/sensitivity curve of the instrument

* A. H. DAVIS: *Engineering*, 1934, vol. 138, p. 663.

* First, Second, and Third Interim Reports of the Committee on the Operation of Mechanically Propelled Vehicles (H.M. Stationery Office, 1935, 1936, and 1937).

† Readings change by about 1 phon if the H.T. volts (180 V) change by $2\frac{1}{2}$%, and by 0·1 phon if the filament voltage (6 V) changes by 10 %.

‡ See W. L. WATTON: *Experimental Wireless*, 1934, vol. 11, p. 17.

correspond to that of the ear at the loudness of the sounds to be measured.

Instruments having weighting networks to ensure that steady pure notes of an equal loudness shall give equal readings on an indicator, have been in use for some time.* Some have been designed for one region of loudness only, whereas others have included, say, three or five networks so that the ear can be simulated at several loudness levels. An adjustment for frequency response is obviously essential in any instrument designed to measure the loudness of sounds; some objective noise-meters apparently make no further attempt to simulate the ear, and are unlikely to deal correctly with intermittent or impulsive sounds.

SPECIFICATION OF OBJECTIVE NOISE-METER

The additional considerations actively borne in mind in designing the present meter were that the response of the ear to single impulsive sounds appears to depend mainly upon the peak disturbance experienced in relation to the threshold for that type of noise, but that the loudness of repeated impulses increases with speed of repetition up to about 50 repetitions per sec.†

It was decided, therefore, to attempt to design an instrument to the following specification, since a meter acceptable in these respects might reasonably be expected to be satisfactory for a wide range of sound:—

(1) The frequency-sensitivity of the meter should be such that, for the loudness concerned, the meter assesses the equivalent loudness of pure notes, irrespective of their pitch with an accuracy greater than that of the average individual human observer.

(2) The meter should assess with similar accuracy the equivalent loudness of sounds of short duration repeated at speeds of, say, 12, 25, and 50 impulses per sec., and single impulses also if possible.

It was considered desirable, as a step towards the attainment of these ends, that—

(3) The meter and indicator should agree approximately with the ear in regard to the rapidity of response.

(a) Frequency-Sensitivity of the Meter

Fig. 2 exhibits curves showing how, according to data for free-air listening obtained by Fletcher and Munson,* the sensitivity of the meter should vary with frequency in order to give equal readings for pure notes of all frequencies at various levels of equivalent loudness, namely 60, 70, 80, 100, and 120 phons. The figure shows also the sensitivity curves of the two scales of the meter, as determined on experimental calibration. The curves have been plotted with a common point at 1 000 cycles per sec. The curves for the meter are in good agreement with Fletcher and Munson's curves for the ear at the levels of 60–70 phons and 80–100 phons respectively, and in very reasonable agreement with the curve for 120 phons, deviations being rarely much in excess of 5 phons —the error normally associated with any individual human observation of loudness.† Thus the meter, when calibrated so as to give the intensity of a 1 000-cycle pure tone in decibels above 0·0002 dyne per cm^2, i.e. so as to give the equivalent loudness of the tone in phons, should be at least as good as any observer in assessing the equivalent loudness of any other continuous pure tones, provided they are of conversational loudness (60–70 phons) or louder, and often it should be very much better.

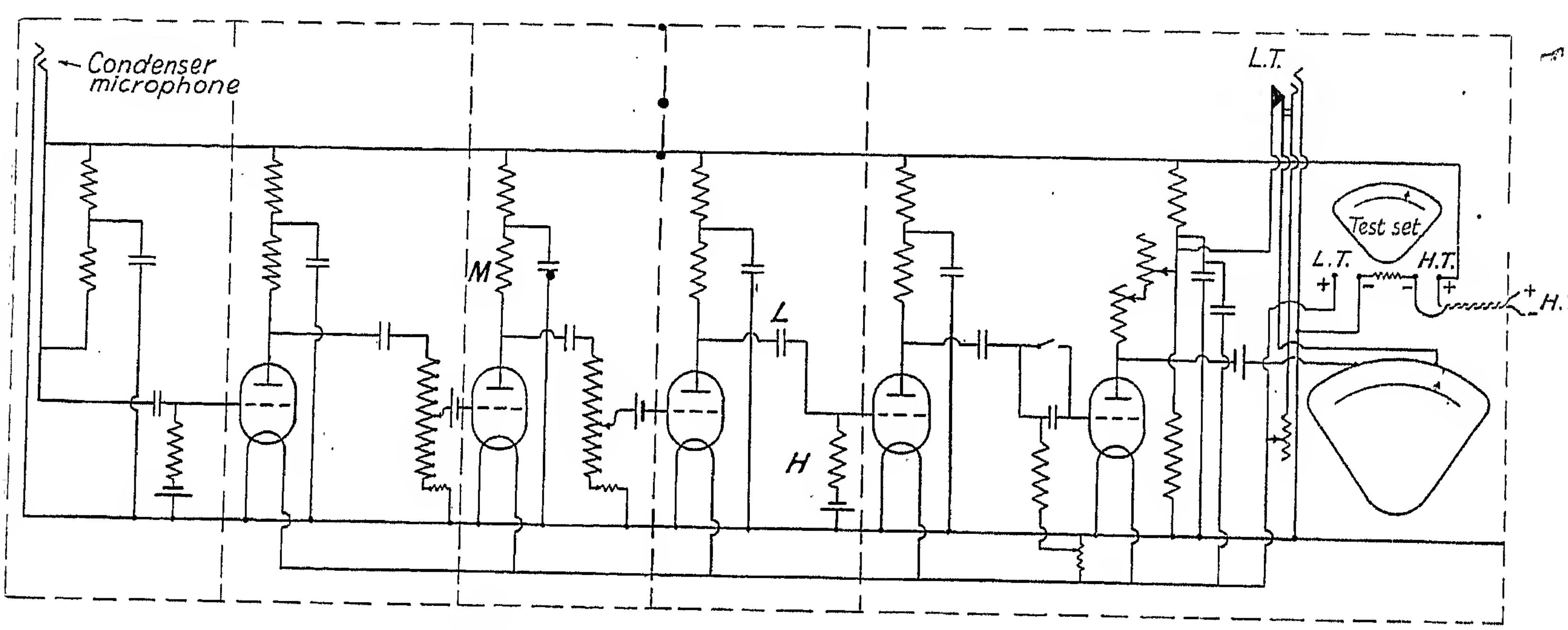


Fig. 1.—Circuit arrangement of objective noise-meter.

(b) Rapidity of Response of the Indicator of the Meter

According to Bekesey,‡ a steady sound applied to the ear does not attain its full loudness until it has persisted

* Brief notes of several, with references, were given by the author in the survey referred to above.

† U. Steudel: *Hochfrequenztechnik und Elektroakustik*, 1933, vol. 41, p. 15.

* H. Fletcher and W. A. Munson: *Journal of the Acoustical Society of America*, 1933, vol. 5, p. 82.

† A review of data for noises is given in *Engineering* (1934, vol. 138, p. 663). Kingsbury gives a table of "variances" obtained in judgments of the equality of the loudness of pure tones of different pitch. A single observation by a given observer deviated on an average by, say, ±3 or ±5 phons from his mean result, and his mean deviated from ±4 to ±10 phons from the average of 22 observers.

‡ *Physikalische Zeitschrift*, 1929, vol. 30, p. 115.

for about 0·2 sec. Cinematograph photographs of the indicator of the noise-meter taken after the sudden application of a sound to the microphone, and also on suddenly connecting the indicator into the noise-meter circuit, showed that the indicator, which was aperiodic, reached within $1\frac{1}{2}$ decibels of its full deflection in 0·2 sec., and thus for steady sounds has approximately the same rapidity of response as the ear.*

(c) Response to Recurrent Impulses

Since, according to Steudel,† the response of the ear to single impulsive sounds appears to depend mainly upon the maximum impulses which the ear experiences in rather less than a thousandth of a second, the meter should act somewhat as a peak meter, fairly rapid in response. It must not be too rapid, for under certain conditions subsequent repetitions would add to the loudness as heard by the ear, whereas they would not increase the reading of a true peak meter. The meter, however, must have an appropriate leak, for the loudness of a slow series of repetitions is less than that of a rapid series. In fact, the leak should be such that the effect of an impulse leaks away only to an appropriately limited extent in $\frac{1}{10}$, $\frac{1}{20}$, and $\frac{1}{50}$ sec. respectively, but leaks away almost completely in a second or so, since repetitions separated by a second or so from the first impulse do not add to the loudness.

The manner in which it was sought to attain the essential characteristics in the present meter was to arrange the circuits so that the rectifying valve of the instrument acted as a rapid but leaking peak meter, the rates of response and decay being adjusted empirically so that the meter gave correct results for the loudness of impulsive sounds of various frequencies of intermittence ranging from 5 to 50 repetitions per sec. Whilst peak meters have been used before, the author believes this is the first time that a leaking peak meter has been used in a condition adjusted to deal best with impulsive sounds.

As a source of impulsive sounds a rattle was employed, of the type in which a spring resting on a toothed wheel delivers blows to the successive teeth as the wheel is revolved. Note was made (i.e. by aural means) of the approximate loudness of a single impulse from a rattle, of impulses repeated at a moderate speed, and of impulses so rapidly repeated as to give an almost continuous sound. The objective noise-meter was then adjusted by trial to give results similar to those obtained aurally. In this adjustment attention was paid to the grid resistance and coupling condenser in front of the rectifier valve. With a grid resistance of 0·5 megohm and coupling condenser of 0·2 μF such as are usual in rectifier circuits, the effect of one impulse on the rattle leaked away so rapidly that it had disappeared before the following impulse occurred. With the same coupling condenser and with the grid resistance removed (grid isolated) the leak was very slow, and the effect of a second impulse was added to the first, even though several seconds had elapsed between them. What was needed was an intermediate rate of leak which would cause impulses to be partially additive if they were rapidly recurrent, but not if the rate of repetition was slow. This result was achieved, after considerable trial with various values of coupling condenser and grid leak, by using a coupling condenser of 0·002 μF and omitting the grid leak. In Fig. 1 the switch before the rectifier short-circuits a 0·002-μF condenser, and is normally open when the instrument is used as an objective noise-meter.

This adjustment increased the reading of the instrument (the meter in each case being set to read correctly for a 1 000-cycle pure tone) by amounts corresponding to about 15 phons for single sharp metallic impulses, about 5–10 phons for rapid (50 impulses per sec.) and slow (12 per sec.) impacts of a duller character, and about 1–5 phons for certain warbling notes and for the bell-like note from a short metal spring bent aside and released. In other words, the importance of the impulse adjustment was greatest for sharp impulses, and became less and less appreciable as the sound approached a continuous pure note. Consistent with this it was found

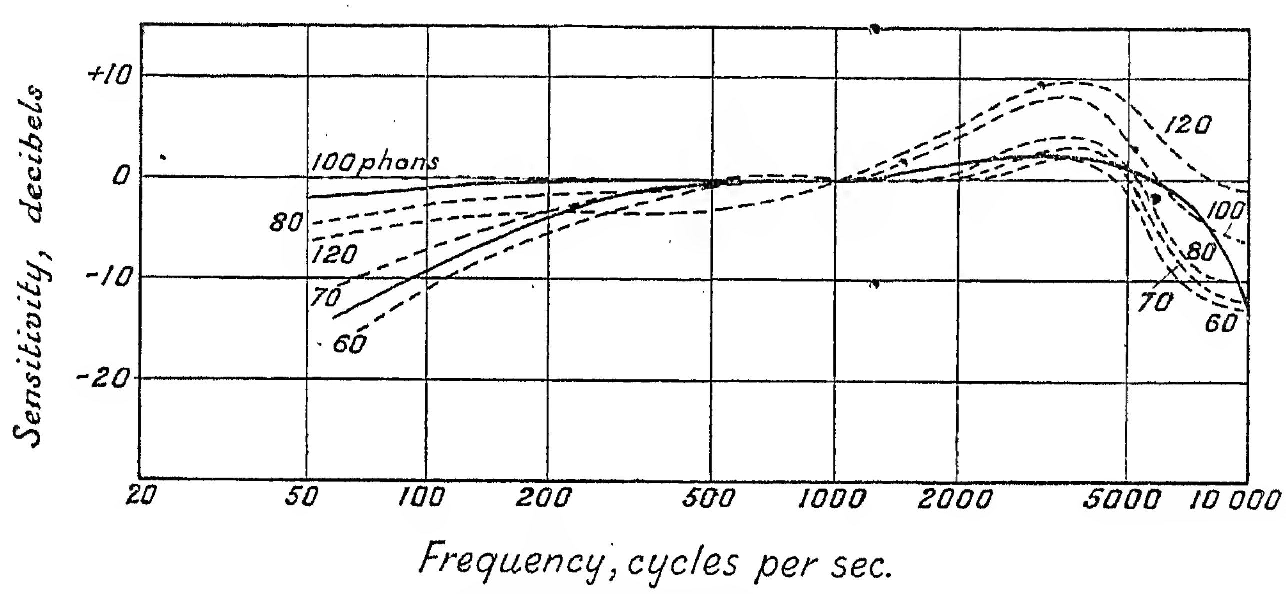


Fig. 2.—Frequency/sensitivity curves of objective noise-meter (full-line) compared with Fletcher and Munson's curves (dotted-line) for the frequency-sensitivity of the ear at various levels of equivalent loudness expressed in B.S. phons.

* Aperiodic indicators of only one-third and one-sixth of this speed appeared to be almost equally satisfactory in the noise meter (1-phon reduction) except when measuring low-pitch impulses at low frequencies of repetition (1 per sec.), for which they read some 4 and 5 phons lower. A lightly damped indicator (log. dec. = 0·04) gave difficulties with its resonance.

† *Loc. cit.*

in field measurements that the effect of the impulse adjustment was small for the noise of a small family motor-car, and of an amount corresponding to 6–10 phons for the more impulsive noises associated with a motor-cycle with pronounced exhaust noise.

For a rattle giving 30 impulses per sec. the noise-meter reading (85 phons), in some early tests, agreed well with average aural measurements of nine observers (83 phons) each using three types of subjective noise-meter, and was well within the range of results (70–95 phons) obtained by the various individual observers. When, however, an attempt was made to obtain aural measurements of isolated impulses (about 1 per sec.) the observations of the nine observers were so widely dispersed (40–88 phons) as to make it clear that the assessment of the loudness of single impulses presents exceptional difficulties to the average observer.*

The relative behaviour of the instrument towards

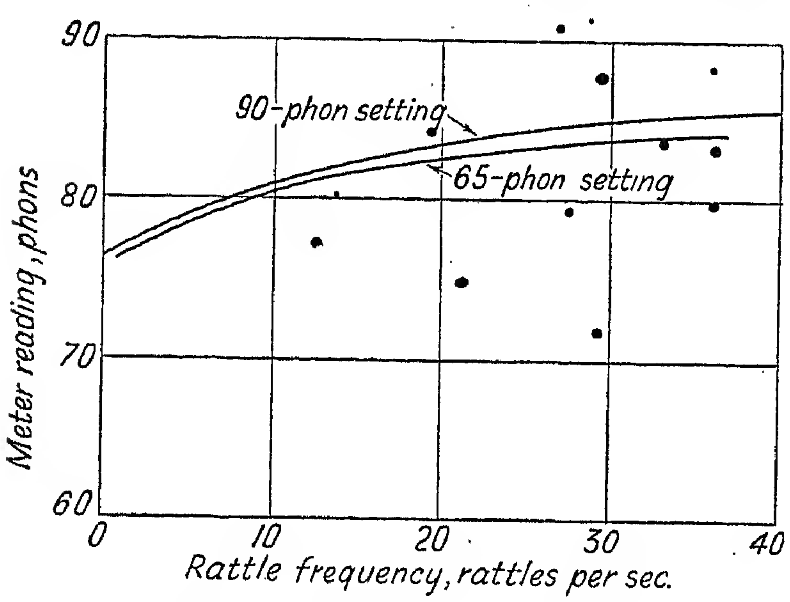


Fig. 3.—Response of noise meter to rattle frequencies.

rattle impulses of various frequencies of repetition is shown in Fig. 3. It will be noted that the curve practically reaches the limit of its rise at 30–50 impulses per sec., when the loudness appears to be nearly 10 phons greater than that of a single impulse. In this respect the noise meter agrees approximately with Steudel's data for a different type of impulse.

IMPULSIVE COMPRESSIONS AND IMPULSIVE RAREFACTIONS

It should be mentioned here that the rectifier of the objective noise-meter is unsymmetrical, and its response depends upon the polarity of the e.m.f. applied to it. In other words, the response of the meter to an impulsive sound depends upon whether the impulse is a compression or a rarefaction, for these would apply e.m.f.'s of different sign to the rectifier. The construction of the meter—i.e. type of microphone, number of amplifier stages, etc.—is such that a compression gives rise to the fullest deflection of the indicator, and it is for fullest deflections that the instrument has been calibrated. Compression noises are frequent in nature, and are represented, for instance, by the explosive noises of exhausts of engines, where the gases are released at high pressure. To be sure of obtaining correct results with rarefactive impulses (such as might be associated with the breaking of a series of evacuated lamp bulbs) it would appear to be necessary to reverse the e.m.f. applied to the rectifier, say by suitable arrangements at an early stage of the amplifier, or by omitting one valve. Such adjustment has not been made.

The extent of the difference between compressive and rarefactive impulses has been studied. Various laboratory noises mentioned below were obtained from a loud-speaker driven by a moving coil in the field of an electromagnet, the arrangements being such that the impulses delivered from the face of the loud-speaker were a series of initial compressions. By reversing the field of the electromagnet the noises become a series of initial rarefactions. Their loudness as heard by the ear was not appreciably affected, but the noise-meter read lower by the amounts shown in Table 1.

Table 1

Type of noise emitted by loud-speaker	Reduction of reading of objective noise-meter on reversing polarizing field of loud-speaker	
	65-phon setting	90-phon setting
Impulsive		
12 pulses per sec.	4	2
25 pulses per sec.	5	5
50 pulses per sec.	7	4
Warbling		
150 ± 50 cycles per sec. . .	0	0
1 800 ± 1 600 cycles per sec.	1	1
Pure		
1 000 cycles per sec. . .	0	0

It is seen that it is only for the really impulsive noises that the difference is significant. For the everyday noises of motor-cycles and motor-cars it was found later that the difference was smaller—less than 2 phons—so that in everyday practice the effect is not likely to be serious.

AURAL MEASUREMENTS OF EQUIVALENT LOUDNESS

In view of the fact that in the above preliminary experiments the instrument had been given a suitable speed of response and had been adjusted to give substantially correct readings for pure notes of various frequencies and for certain impulsive sounds repeated at various rates, it was anticipated that the meter should correctly assess the equivalent loudness of a wide range of sounds. It was therefore tested by measuring with it the equivalent loudness of various complex sounds, which were measured at the same time aurally by several observers, usually 9 or more.

By a recently-fixed British definition* the equivalent

* The acoustimeter indicated that the impulses varied in loudness from 76 to 82 phons. This result is well within the dispersal range of the results of the various individual observers, although it differs appreciably from the mean of the very scattered aural observations.

* See Definition 2017, "British Standard Glossary of Acoustical Terms and Definitions," B.S.S. No. 661—1936).

loudness of a sound is measured by the intensity level of a pure tone of frequency 1 000 cycles per sec. which is judged by a normal observer to be as loud as the sound. In the comparison the pure tone and the noise are heard in free air alternately for periods of a second or two, the observer facing the sources and listening with both ears. When the intensity of the standard tone is n decibels above a certain reference intensity* near the threshold of hearing, the noise under measurement is said to have a loudness of n British Standard phons.†

This technique of listening, however, has limitations for field measurements on many classes of noise. With some noises—for example, noises in aircraft—it is not easily possible to arrange for the noise to alternate with a standard note, and with others it is not practicable to employ a free-air standard tone. Consequently other methods of estimating equivalent loudness are employed in commercial and laboratory practice. In one the observer listens to the noise with one ear and to a standard tone of some kind with the other, the tone being of adjustable intensity and applied to the ear by means of a telephone earpiece. He adjusts the loudness of the standard note until he is equally aware of the note and of the noise when he hears the two simultaneously.

It is often assumed that such subjective meters will give the same results as the standard technique if the meters are calibrated to give correct readings when the "noise" observed is the standard 1 000-cycle tone. In the present work, commenced before the standard procedure was decided upon by the British Standards Institution, a number of early measurements with various subjective meters revealed that although the meters gave substantially the same results as the standard technique for a number of noises, they did not do so for others. It was in fact found to be unsafe to assume that the meters will give the same results as the standard technique if they are used with a procedure involving simultaneous listening to the noise and to the meter. A technique of alternate listening evolved during tests of motor horns appeared, however, to be more satisfactory.

In the case of noises, therefore, which cannot be started and stopped regularly at intervals of 1 second or so, and which consequently cannot be arranged themselves to alternate with a standard sound, the use of electrical or film records of the noise suggests itself as a helpful intermediary. In certain of the tests mentioned below the noise was picked up by a microphone, and reproduced at correct volume on a loud-speaker arranged, by suitable switching, to emit the test noise and the 1 000-cycle reference tone alternately at 1-sec. intervals.

NOISES STUDIED

(a) "Laboratory" Produced Noises.

For the purpose of testing whether the meter, as adjusted to give correct values for the equivalent loudness of pure tones of moderate loudness, would correctly assess the equivalent loudness of a wide range of complex and intermittent sounds, a number of noises of representative type were produced in the laboratory. They were studied aurally by the standard technique. They included:—

(1) Pure tone of frequency 1 000 cycles per sec. (standard of reference).

(2) Impulsive low-pitched "throbbing" note, the frequency of the throbs being 12 per sec. and the sharpness of the impulses similar to those of a motor-cycle exhaust, or perhaps rather sharper.

(3) Similar to No. (2), the frequency of the throbs being about 25 per sec.

(4) Similar to No. (2), the frequency of the throbs being about 50 per sec.

(5) Pure warbling note, low pitch, of which the frequency varied 5 times per sec. over the range 150 ± 50 cycles per sec.

(6) Pure warbling note of which the frequency varied 5 times per sec. over the range $1\,800 \pm 1\,600$ cycles per sec.

(7) Low-pitched air-blown motor horn, blown continuously.

Several of the sounds Nos. (1) to (6) were produced with the aid of a loud-speaker—a moving-coil instrument with a conical diaphragm. The warbling notes, Nos. (5) and (6), emitted by the loud-speaker were derived from gramophone records. The intermittent low-pitched noises, Nos. (2), (3), and (4), were derived from a neon lamp oscillator (12–50 cycles per sec.) giving a very complex output. The circuits were such that the impulses delivered by the loud-speaker were compressions, the diaphragm moving forwards first at each impulse. The remaining noise, No. (7), was due to a motor horn blown by means of a continuous air supply.

The wave-forms of the noises are given on the left-hand side of Fig. 4 (see Plate, facing page 256), in association with $\frac{1}{50}$-sec. time marks except in the case of the pure tone. Clearly the wave-forms represent a number of features which occur in oscillograms of everyday noise.

Band analyses of the sounds are given in Fig. 5. They were obtained with the aid of band-pass filters, each passing a band of frequencies approximately an octave wide.

A full analysis of the nominal 50-cycle intermittent tone revealed that the components of the sound were exact multiples of the fundamental, all harmonics of the fundamental being present from the 1st to the 30th with the exception only of the 8th and 28th. Similar analyses were obtained with the 25-cycle impulsive noise, the 8th, 12th, and 22nd harmonics being missing in this case.

The sounds were produced in a chamber about 9 ft. by 12 ft. by 9 ft. (high) in size, the surfaces of which were lined internally with a 6-in. layer of eel-grass, supplemented by a 1-ft. inner lining of closely-packed layers of cotton wool hanging edgewise. The absorbent lining ensured that the chamber was acoustically dead, so that the intermittent sounds were observable without the merging effect of reverberation.

In the test the source of noise was placed near one side of the chamber, and the observer, with his head in

* Corresponding to an r.m.s. sound pressure of 0·0002 dyne per cm².

† Until recently the term "decibel" was used in England to express the equivalent loudness of a sound and also its intensity. A criticism of the old procedure and a suggestion for adopting the "phon" for loudness measurements was published by the present author in the *Proceedings of the Physical Society* (1934, vol. 46, p. 631).

a standard position about 4 ft. distant, listened alternately to it and to the reference tone. When the observer had aurally assessed the equivalent loudness of the sound, the noise-meter was substituted* for the observer and a measurement of loudness made with it.

Table 2 shows the mean results obtained in a series of tests† when readings of the acoustimeter were compared with the aural measurements of from 9 to 12 persons, using the standard technique of comparison with the loudness of a 1 000-cycle tone. In each case the noise and the reference tone were heard alternately for 1-sec. intervals, and for all noises except that of the horn the same loud-speaker served as the source of the noise and of the reference tone. In one set of observations [Series (A)] the observer adjusted the intensity of the standard tone himself until he judged it to be as loud as the noise. In another [Series (B)] the intensity of the standard tone was controlled by an independent operator outside the observation chamber. The noise and a reference tone were sounded alternately twice, and the observer recorded which was the louder. The strength of the reference tone was then altered by the operator and the observations repeated. From a study of the observers' records at various strengths of the reference tone the equality point was deduced. The two techniques usually gave very similar results. The method of outside control takes rather longer than that in which the observer makes his own adjustments, and in some cases where time was limited only the latter technique was employed.

Results relating to the case when observers adjusted the reference tone themselves are given in Fig. 6. Each point in the figure represents a measurement by one observer plotted against the corresponding reading of the objective noise-meter as adjusted for the level of about 65 phons. The variation between observers is clearly brought out in the case of all noises measured. The extent to which the objective noise-meter accurately represents the average judgment is indicated by the extent to which the line drawn is representative of the average trend of the various results. Clearly the meter gives results within the range of observations obtained from aural observers, and, particularly for loudnesses in the region above 80 phons (for which it was specially sought to make the meter reliable), is better than any randomly-chosen individual observer in assessing the loudness of any of the varied noises concerned. The line is possibly 2 phons lower than the best average, the meter slightly under-estimating the loudness of the noises.

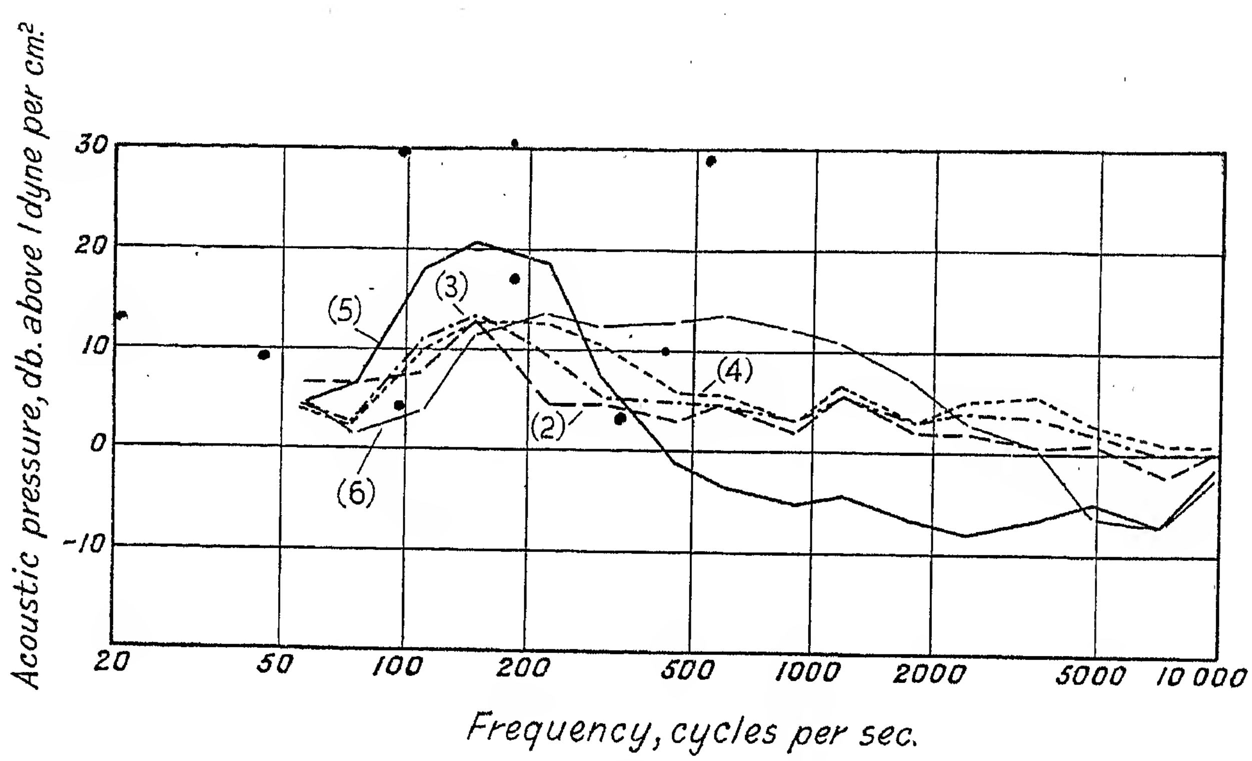


Fig. 5.—Band analyses of various laboratory noises.

Noise No. (2). Impulsive. Noise No. (4). Impulsive.
Noise No. (3). Impulsive. Noise No. (5). Warbling.
Noise No. (6). Warbling.
(Further details of these noises are given on page 253.)

When the frequency response of the instrument was altered to agree with the ear at a loudness of 90 phons. instead of 65 phons, slightly higher readings (+ 4 to + 6 phons) were obtained on the objective meter for the intermittent noises and the low-pitched warble, but with the horn and the high-frequency warble the changes (0 to + 1 phon) were smaller. With the 90-phon adjustment the meter slightly over-estimated the loudness of the noises instead of under-estimating as before, but again was better than the average randomly-chosen individual.

(b) Everyday Noises

As a supplement to work on the controlled laboratory noises already described, a number of measurements were made—by the objective meter and by aural

* The noises were not very different (0 to 2 db.) if measured in the presence of the observer, but the 1 000-cycle note was slightly more intense (2–4 db.) when so measured.

† Some earlier tests of intermittent noises have been excluded. Their inclusion would not have affected appreciably the average agreement of the acoustimeter with aural observations, but it is only with the later observations that all the necessary experimental precautions are known to have been observed.

observers—of a few types of everyday noise of which complaint is often made. In these it was not always possible to make the aural observations by the standard relate only to such standard measurements. Some further results for motor horns obtained by an apparently satisfactory technique of alternate listening with a sub-

Table 2

COMPARISON BETWEEN SUBJECTIVE* AND OBJECTIVE MEASUREMENTS OF THE EQUIVALENT LOUDNESS OF VARIOUS NOISES

No.	Noise Type	Equivalent loudness, B.S. phons					
		Aural observations of 9 or more observers				Reading of objective meter† at setting	
		(A)		(B)			
		Mean	Range	Mean	Range	65 phons	90 phons
(2)	Impulsive, 12 cycles/sec.	90	75–97	92	84–98	84	87
		87	77–100	89	77–97	90	95
		67	52–76	69	61–79	63	68
(3)	Do., 25	93	87–102	94	88–103	89	92
		90	80–98	93	90–100	93	96
(4)	Do., 50	94	86–102	96	88–103	92	93
		93	87–100	94	89–100	96	
		73	55–83	76	64–82	69	70
(5)	Warbling, 150 ± 50 cycles/sec. ..	86	81–89			86	90
				87	81–93	86	90
		90	84–97	93	85–97	89	95
		65	58–72	69	60–78	69	75
(6)	Do., 1 800 ± 1 600	90	87–93			87	89
				89	82–89	87	87
		91	85–97	92	85–95	89	93
		70	60–77	71	59–76	67	71
(7)	Motor horn	92	87–96			91	92
				93	89–97	91	92
(8)	Motor-cycle, 18 ft., slow; fore ..	89	85–92			87	91
				94	85–100	87	91
(10)	Do., aft	92	87–98			93	97
				95	85–102	93	97
(9)	Do., medium; fore ..	93	87–98			91	94
				98	90–100	91	94
(11)	Do., medium; aft ..	97	93–101			97	101
				100	90–100	98	102
(18)	Motor-car, 18 ft.; fore	82	72–91	—	—	85	86
(19)	Do., aft	77	75–82			76	81

* *The subjective method* consisted of alternate listening (1-sec. alternations) to the noise and to a free-air 1 000-cycle note, using two techniques in which:—
(*a*) The observer himself adjusts the loudness of the 1 000-cycle tone until he judges it to be as loud as the noise.
(*b*) The observer merely records whether a 1 000-cycle tone presented to him is louder or quieter than the noise. The intensity of the note is then altered, and a new judgment made.

† Noise intensities were not exactly the same for all observers, and slight corrections to the aural observations were made where necessary to allow for this.

technique. However, the noises referred to in Table 2 and in Figs. 4–7 are those of which equivalent loudnesses were measured (in a reproduced condition, if necessary) by the standard technique, and the results given in them jective meter are given in Table 3, but are not included in Table 2 or in the Figures. Certain cases where a subjective meter and simultaneous listening were perforce used are mentioned in the Appendix.

(i) **Motor horns.**

Some open-air measurements of the loudness of the sounds emitted by several types of motor horns were made by means of subjective meters. At first the technique usual with such meters was employed, and per sec. respectively), and also a third giving a very low-pitched complex tone.

Although the objective noise-meter gave results usually within the range of measurements with subjective meters, and not far removed from the average, the

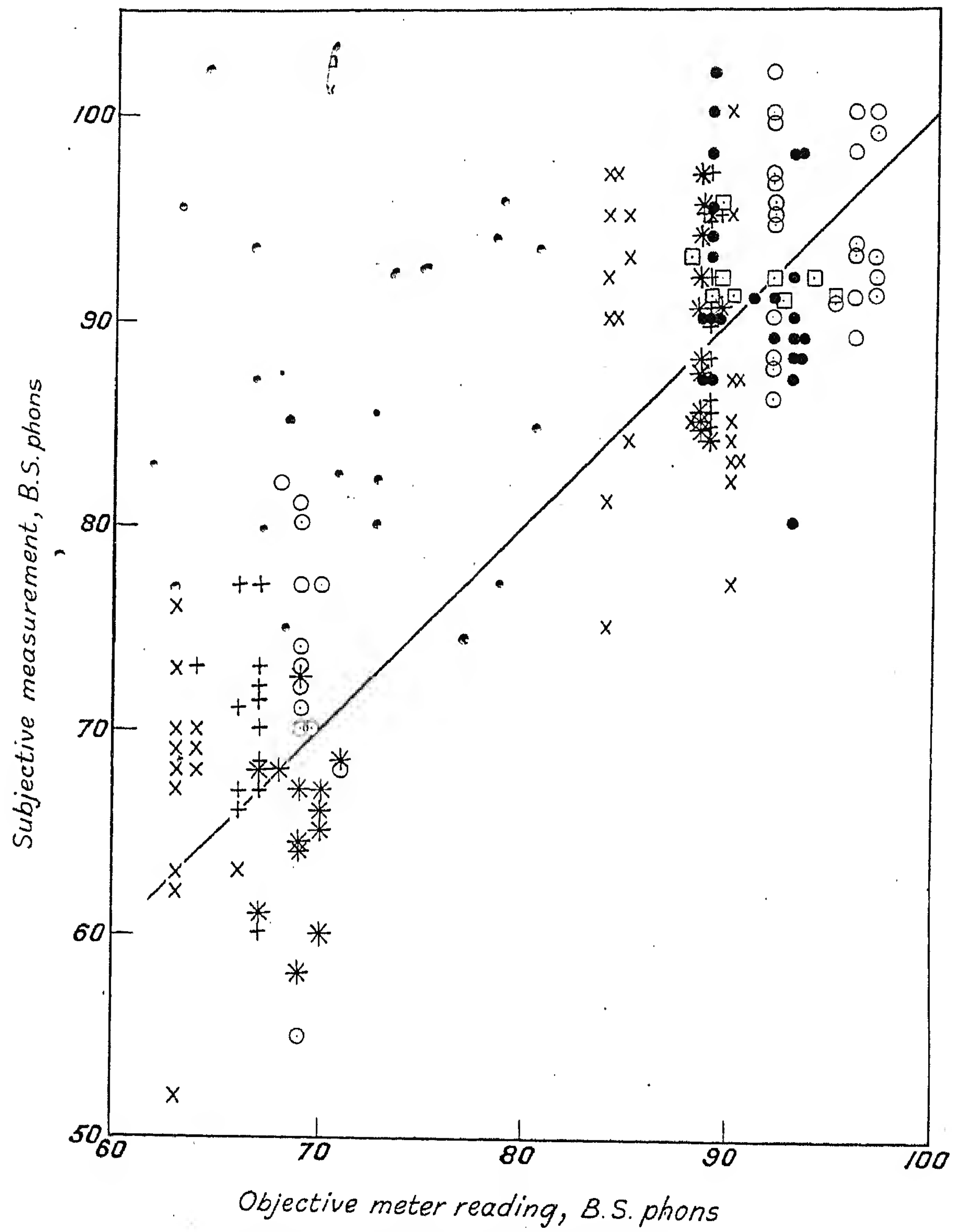


Fig. 6.—Relation between subjective and objective measurements of various noises. Subjective measurement: Alternate listening to free-air 1 000-cycle tone and to noise, observer adjusting reference tone to equality with noise. Objective meter: 65-phon setting.

× Noise No. (2): Impulsive. • Noise No. (3): Impulsive. ⊙ Noise No. (4): Impulsive. * Noise No. (5): Warbling. † Noise No. (6): Warbling. ⊡ Noise No. (7): Motor horn.

(For key to these noises, see Table 2.)

Each point represents one measurement by one observer.

the horn was heard in one ear whilst the comparison tone of the meter was heard simultaneously in the other. Since it was anticipated that simultaneous listening might lead to difficulties where, say, a component of the horn noise was close in pitch to the tone of the meter, two subjective meters of different pitches were separately employed (pure tones of 640 and 800 cycles

various subjective meters did not all give the same results, differences corresponding to 10 to 20 phons being observed. The anomaly did not disappear when the measurements were repeated at the same distance, or at different distances. A check on the subjective meters themselves, in which the loudness of the tone from each was compared in turn with the loudness of the tone

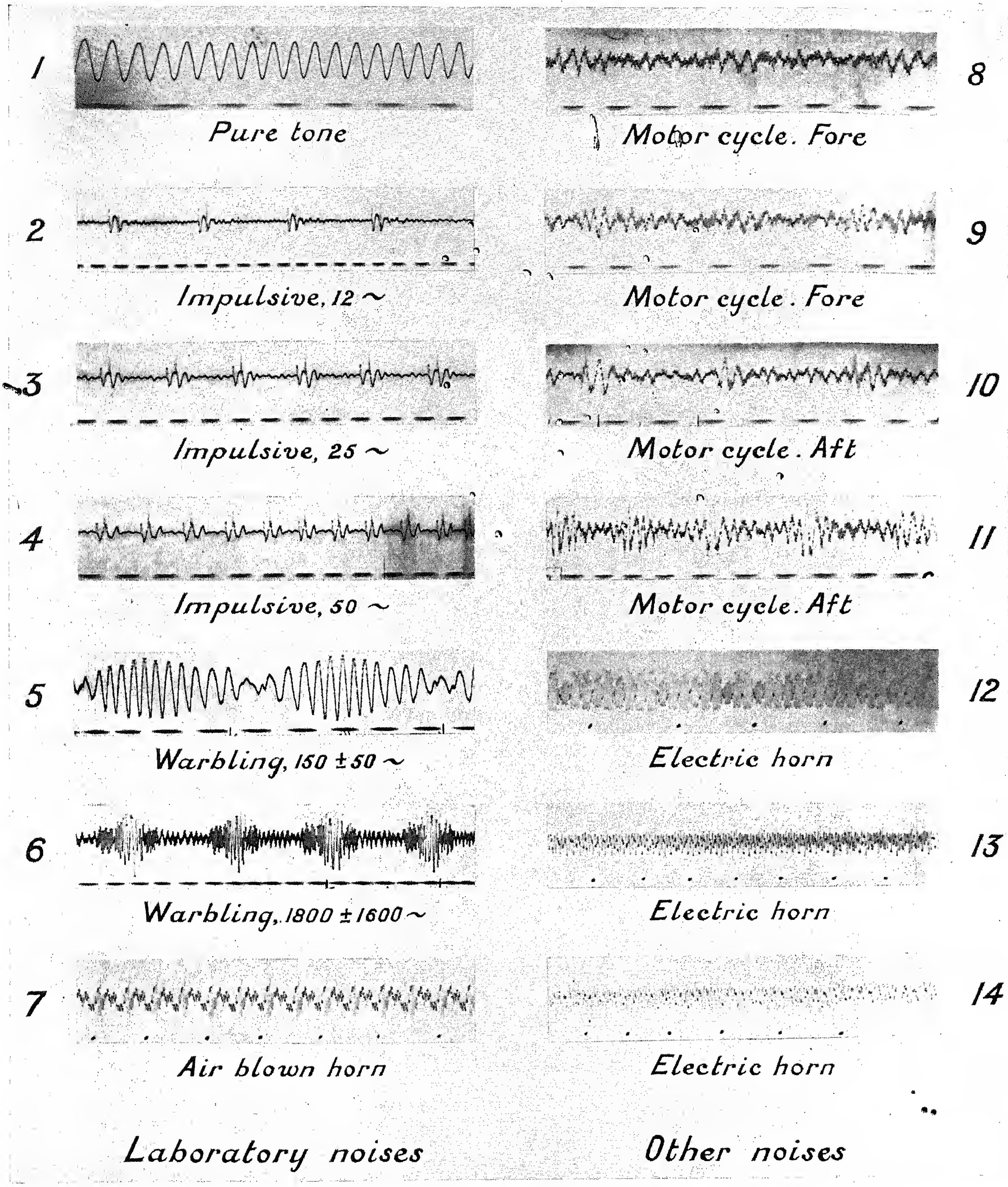


Fig. 4.—Wave-forms of various noises.

from the others, showed that the tones of the meters were equally loud when the meters gave equal readings. Thus it was clear that when the various meters were adjusted to give tones as loud as a given horn heard at the same time, they were not as loud as one another. It was therefore suspected that possibly the hearing of the tones of some of the subjective noise-meters was being interfered with by prominent components of the very complex sounds emitted by the horns. To avoid this interference, recourse was had to a technique of alternate listening.* In this technique the observer faced the motor horn, which was sounding in short bursts of 1 sec. or so followed by similar intervals of silence. During the intervals in which the horn was sounding the observer listened to it with both ears: during its silences he applied to one ear the earpiece of the subjective meter and listened to the comparison tone of the meter, which he adjusted as time went on until he judged it to be as loud as the noise from the motor horn. For interpreting the measurements the subjective meter was calibrated against a free-air 1 000-cycle note by the same procedure.†

The horns were:—

Noise No. (12). Powerful electromagnetic horn, in which an armature strikes a magnet and excites a stiff diaphragm, free at its edges. Analysis indicated the components of the sound to be exact harmonics of the fundamental (375 cycles per sec.) and to be present, with few omissions, up to the 26th, the most prominent being those (1 875 to 3 000 cycles per sec.) in the region of the free tone of the diaphragm.

Noise No. (13). Twin horn, consisting of electromagnetically-driven tuned diaphragms, with horns tuned a major third apart. The sound consisted of two chief and two subsidiary harmonic series of components, the fundamentals being musically related. The sound was mainly in the region 300–2 000 cycles per sec.

Noise No. (14). Similar to No. (13), but louder.

The analyses were made by a beat-tone method, and the harmonics were identified within the limits of accuracy of the scale of the analyser.

The procedure of alternate listening to these horns removed all anomalies from the results, and the subjective meters at last agreed with each other.

On the basis of these experiments the equivalent loudnesses of the horns are expressed in Table 3 in phons, but it should be emphasized that each figure is in fact the true equivalent loudness of the 1 000-cycle tone which was judged indirectly (instead of directly) to be as loud as the horn noise, each being heard alone with two ears in free air. Each figure is thus the true equivalent loudness of the horn, if it can be assumed that the sounds which were judged by alternate listening to be as loud as the same subjective-meter tone were as loud as each other. The fact that the results obtained with different comparison tones were mutually consistent and, within the limits of accuracy of such experiments, independent of the type of subjective intermediary used, is strong support for the assumption.

As will be seen from Table 3, the subjective meters agree substantially with each other, and the objective meter agrees with them all. The results obtained with the 90-phon adjustment of the objective meter were about 1 phon lower.

(ii) Noises of motor vehicles: exhaust noise.

Arrangements were made for verifying that the meter read correctly for such motor noises as could conveniently be subjected to test. To meet the difficulty that aural measurements of the loudness of vehicle noise should be made under the standardized conditions of alternate listening, the motor-cycle or motor-car under measurement was stationary on open ground, with its engine running steadily. A microphone at a distance of 18 ft. picked up the sound, and transmitted it in electrical form to a rotating switch so arranged that a loud-speaker in the lagged test chamber emitted alternately, at 1-sec. intervals, the reproduced motor noise and a pure 1 000-cycle note.* The circuits were so arranged that the first pulse from the loud-speaker diaphragm was a compression to correspond to the compression which would be sent out from an engine exhaust as each pulse of compressed gas was ejected into the air. As was mentioned earlier, however, the noises did not prove to be of a type in which this precaution was important.

That the acoustical reproduction of the noise was reasonably satisfactory was noted aurally, and also by comparing an analysis of the motor noise with that of the reproduced noise, as emitted by the loud-speaker. For the analysis, owing to the variability of the noise,

Table 3

Comparison between Subjective* and Objective Measurements of the Equivalent Loudness of Motor Horns measured at 250 ft.

Noise meter	Equivalent loudness of horn (B.S. phons)†	
	No. (12) horn‡	No. (14) horn‡
Subjective meters.		
640	92 (88–93)	83 (76–86)
800	91 (88–98)	83 (77–93)
Complex	94 (90–98)	86 (83–89)
Objective meter .. .. (65-phon adjustment)	91–94	83–87

* Subjective results: Average for 6 observers listening alternately to horn and to earpiece of subjective noise-meter.
† Equivalent loudness is phons inferred indirectly, as stated in text.
‡ Horn No. (13) could not be used further for a satisfactory test, as it was becoming very variable in action. Such measurements as were possible with No. (13) (82–87 phons, as against 84 phons on the objective meter) confirmed the agreement between subjective and objective measurements.

* Since this work was completed B. A. G. Churcher and A. J. King have described before The Institution a two-telephone subjective meter by means of which alternate listening is achieved (see vol. 81, p. 69).
† This calibration differs from the normal technique of simultaneous listening not only in that alternate listening is employed, but also in that the 1 000-cycle tone is listened to with two ears instead of one. The two calibrations differed by about 3 phons.

* Some measurements obtained with the aid of three aural audiometers of the telephone type, using the technique of simultaneous listening, gave results which were several phons low at the rear of the motor, where the impulsive and somewhat irregular "popping" of the exhaust was pronounced.

the distribution of sound in various octave frequency-bands was observed.

Cooling air was blown over the engine whilst the work was in progress, and for the motor-cycle the engine speeds corresponded to speeds (say, 30–50 m.p.h.) at which a vehicle might run on roads. Since, however, the engine has to idle for a considerable time whilst aural measurements are being made, and since a large number of observers is necessary, it was impracticable to run even the motor-cycle at higher speeds without special cooling arrangements.

The comparison, for the reproduced sounds, between readings of the objective meter and aural measurements made with the standard technique of alternate listening is shown in Table 2 [Noises Nos. (8)–(11), (18), and (19)]. The meter gave results well within the range of the standard aural measurements; and, with the "65 phon" setting for which adjustments were originally made, gave results within ± 2 phons of the average aural measurements obtained by the technique adopted for Series (A).

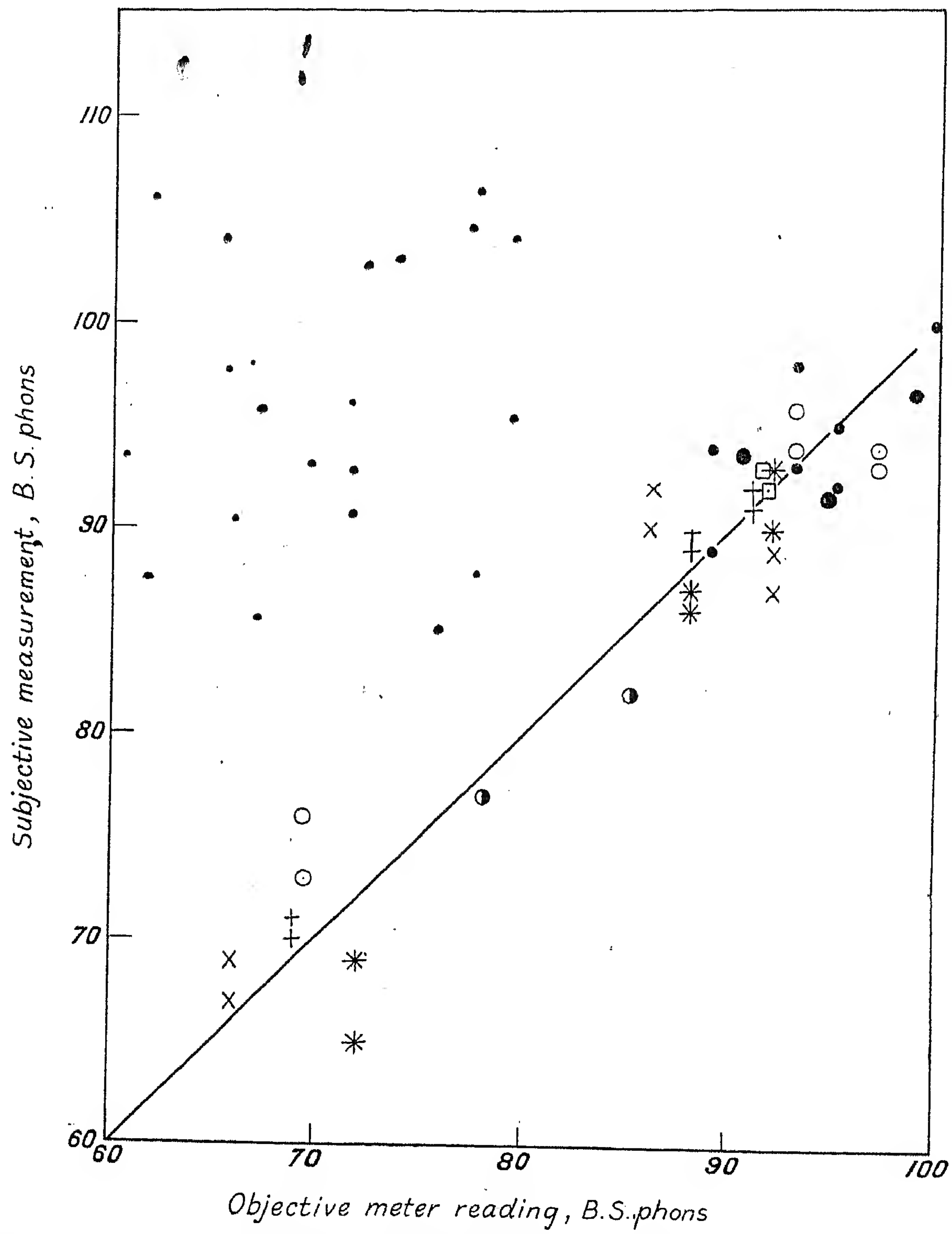


Fig. 7.—Relation between subjective and objective measurements of various noises. Subjective measurement: Alternate listening to free-air 1 000-cycle tone and to noise; two techniques. Objective meter: Mean of two settings.

× Noise No. (2). Impulsive.
● Noise No. (3). Impulsive.
⊙ Noise No. (4). Impulsive.
✳ Noise No. (5). Warbling.
† Noise No. (6). Warbling.
⊡ Noise No. (7). Motor horn.
• Noises Nos. (8) to (11). Motor-cycle.
◑ Noises Nos. (18) and (19). Motor-car.

Each point represents the average result for several observers on a single occasion.

SUMMARY OF RESULTS FOR VARIOUS NOISES TESTED BY THE STANDARD AURAL TECHNIQUE

Fig. 7 collects together graphically the average results for the various noises which were studied aurally by the standard technique, and for which full data are given

in Table 2. Each point represents the average meter readings for one of the noises, in comparison with the mean of the aural measurements of 9–12 observers taken on the same occasion. The line drawn is the one which would be obtained if the objective meter read correctly, and is seen to be an excellent average curve through the various experimental points.

If the meter readings for the 65-phon setting are plotted, the points lie some 0–2 phons to the left of their positions in Fig. 7; readings for the 90-phon setting lie some 0–2 phons to the right. The general inference is that both the 65- and the 90-phon settings of the noise-meter are much better than any randomly-selected individual aural observer for the varied noises tested in this region, but that an average of these settings—say, a 75-phon setting—would be better still.

On detailed examination of Table 2 it is revealed that whilst the two procedures adopted in carrying out the aural standard measurement gave results in fairly close agreement, Series (B) technique frequently gave the higher reading. At the present early stage in the science of the aural measurement of the equivalent loudness of noise the author is not prepared to regard the difference as significant.

On close inspection of Fig. 7 it is seen that in the upper region of loudness, i.e. in the region of, say, 80–100 phons, the meter is in very satisfactory agreement with the average of aural results for the various noises, being always well within the range of aural observations by individual observers, and closely representative of the mean of the results obtained on different occasions for the same noise by groups of 9–12 observers. It was actually for this region, which ranges upwards from the loudness of full conversational speech and lies near the borderline separating noisy from moderately loud vehicles, that the instrument was originally adjusted.

In the lower region of loudness (65–75 phons), whilst on the average the meter gives results of the right order, there appears to be a tendency for it to read too low or impulsive noises and too high for the low-pitched warble note. This may be due to experimental error, and might be counterbalanced in due course if several series of results were obtained. However, in a number of simple experiments in which equally loud impulsive noises and low-pitched warbling noises were equally reduced in intensity, the impulsive noises appeared to fall off least in loudness. The author therefore suspects that the difference in the 65-phon region of Fig. 7 is real, and reserves to the future the study of objective noise-meters at these and lower levels of loudness. It may be that the importance which the ear attributes to impulsiveness may vary with the loudness,* just as the relative response of the ear to sounds of different frequencies depends on the loudness.

READINGS OBTAINED WITH OTHER NOISE METERS

As a test of the general reproducibility of the construction of the noise-meter, the "laboratory" noises were measured (*a*) by means of the acoustimeter which is the subject of this paper, and (*b*) by means of another acoustimeter made by a commercial firm from a specification of components which had been given to them. The sensitivity curves were generally similar to those given for the first meter but not identical, the commercial meter being some 1–2½ phons less sensitive to the low-frequency range 500–50 cycles per sec., and somewhat defective (5 phons) in the region of 4 000–8 000 cycles per sec. The commercially-produced instrument was tested without adjustment. It was calibrated to read correctly for the standard (1 000 cycle) note, and when it was compared with the standard meter on noises Nos. (2) to (7) in Table 2 the two meters gave results for equivalent loudness which were either identical or which agreed within 1 phon. In a wider series of comparisons differences of 2 phons were unusual, and the greatest difference noted was about 3 phons.

When commercially-obtainable noise meters of other types and makes were tested on the noises mentioned they were found to read approximately correctly for the 1 000-cycle note, but to read about 15–30 phons too low for the various low-pitched impulsive noises, and 5–10 phons too low for the warbling notes. One of the meters was claimed to have been adjusted for impulsive sounds. Any adjustments which had been made in the meters to deal with impulsive noises were clearly inadequate, however, and some test of this aspect appears to be desirable where a meter is to be relied upon to compare steady and impulsive sounds.

In this connection it may be mentioned that certain standards for sound-level meters recently tentatively proposed* do not deal with this feature, although they deal with frequency characteristics and rapidity of response. Consequently, meters which conform to the standards appear to be able to give very low results for impulsive sounds, judged by the standard aural technique described above, and would probably fail to compare the loudness of sounds of different degrees of impulsiveness. Indeed, two sound-level meters of different makes which were understood to conform closely if not completely to the suggested standards for such meters were compared with the N.P.L. objective noise-meter on the warbling and impulsive "laboratory" noises employed in the present research. One was found to be correct for both types of warbling noise, at two levels of loudness (70 and 90 phons), whereas the other read 5–13 phons too low. On the three types of impulsive noise (levels 70 and 90 phons) both sound-level meters read much lower than the N.P.L. objective noise-meter, one being on the average 20 phons lower and the other 30 phons lower. The evidence that the readings of the N.P.L. instrument are equal to the equivalent loudness of these noises in B.S. phons is given earlier in this paper.

CONCLUSION

For the varied noises studied in this paper the meter described herein, constructed to the general specification indicated above, agrees well with the ear for noises of equivalent loudness of 80 phons or greater, and to a lesser extent for noises of equivalent loudness down to 60–70 phons. The best adjustment for the frequency

* This observation appears to be in general agreement with the experience that an observer's awareness of a faint sound near the threshold of audibility is considerably increased when the sound is interrupted.

* R. G. McCurdy: *Electrical Engineering*, 1936, vol. 55, p. 260.

response appears to be that associated with Fletcher and Munson's work on hearing in the region of 75–80 phons equivalent loudness, although adjustments to levels of 65 and 90 phons gave results which were well within the range of average individual aural measurements. Finally, whilst the present meter is reasonably satisfactory for the varied types of moderate and loud noise mentioned above (pure, warbling, complex, impulsive), and may therefore be expected to be satisfactory for a wide range of noise measurements, only accumulated experience can apply the final test of its general applicability within the loudness region for which it was designed.

ACKNOWLEDGMENTS

The author desires to express his indebtedness to Dr. G. W. C. Kaye, Superintendent of the Physics Department of the National Physical Laboratory and Chairman of the Ministry of Transport's Departmental Committee on "Noise in the Operation of Mechanically Propelled Vehicles," at whose suggestion actual motor-vehicle noises were included and studied fully despite the difficulties of aural measurement; to Mr. N. Fleming, M.A., and other members of the staff of the Physics Department for help in connection with numerous aural and calibrational measurements involved; and to Mr. E. G. Butcher, B.Sc., for valuable assistance with the experimental arrangements and observations throughout the research. Mr. R. Berry had greatly assisted the author with the design of the portable acoustimeter which formed the basis from which the present objective noise-meter was developed.

APPENDIX

Supplementary Comparisons between the Objective Meter and Aural Measurements

In certain cases, measurements of noise have been made by the meter where it was impracticable to make aural measurements by the standard technique, but in which simultaneous listening to a reference tone in a telephone earpiece was possible. The general results are indicated below, on the assumption that a subjective meter calibrated against a 1 000-cycle pure tone will correctly assess the equivalent loudness of other noises. The present paper shows, of course, that it will not always do so.

Exhaust noise.

For a certain aircraft engine running on a test bench, with one bank of cylinders silenced by elaborate underground arrangements and the other emitting 112 explosions per sec. through an open exhaust or through a silenced exhaust, results obtained by 3 observers with the technique of simultaneous listening (using subjective meters having three types of reference tone) agreed satisfactorily with the objective meter in the case of the open exhaust (110 phons) and in the cases when various types of silencer were applied to the exhaust (85–100 phons).

Possibly, in the measurement of exhaust noises, difficulty with simultaneous listening is not great when the frequency of the exhausts is as high as in the present case.

Noise transmitted through floors.

A large number of observations were made, in a somewhat reverberant corridor below a certain floor, of the equivalent loudness of sounds arising from impacts delivered upon the floor in the room overhead, under various conditions of floor finish. The impacts were delivered at a rate of about 4 per sec., and were of two types; one corresponded to persons walking heavily in rubber-heeled boots, and the other to harsher noises produced by boots heeled with hard material. The structural floor was of concrete, and the finishes included carpet and a 2-in. concrete floor finish "floating" on rubber pads of various dimensions. The subjective measurements were made by 9 observers by means of a Barkhausen-type subjective meter, and so may not be exactly comparable with those which would be obtained by alternate listening with the standard free-air technique. As might be expected from comments upon slow impulses made earlier, the average deviation of any aural observer from the mean (7 phons) was rather greater than is usual with simple noises. For noises of moderate loudness, ranging from about 60 to 80 phons, the meter was in good agreement with the aural observations, being within 1 to 4 phons, but it gave too high a reading (54 phons, as against 37 phons aural) for a light booming sound due to rubber-shod impacts on a floor finish composed of 2 in. of concrete floating on rubber pads on the structural floor. That it incorrectly assessed this low-pitched, quiet, booming note is to be expected, in view of the fact that the equal-loudness curves of the ear change markedly with intensity in the region of low-pitched notes of low intensity. Even so, the objective meter agreed with the average better than one of the 9 aural observers.

[The discussion on this paper will be found on page 275.]

THE CIRCUIT NOISE-METER (PSOPHOMETER) AND ITS APPLICATIONS

By H. R. HARBOTTLE, B.Sc.(Eng.), Member.

(*Paper first received* 24*th September*, 1937, *and in final form* 15*th January*, 1938; *read before the* METER AND INSTRUMENT SECTION 4*th February*, 1938.)

SUMMARY

The circuit noise-meter (or psophometer) is an instrument which has been designed for measuring the disturbing effect of power induction on telephone conversation. Measurements have indicated that some form of frequency weighting in the instrument is desirable. The proposed C.C.I.F.* specification for the instrument is quoted and discussed. Some useful applications of the psophometer are given. The limitations of present models as applied to other types of noise are reviewed.

CONTENTS

HISTORICAL

The circuit noise-meter or, more explicitly, the telephone line noise-measuring set, is known internationally as the psophometer. It is an instrument which has been designed to indicate the disturbing effect of steady electrical noises on telephone conversation. The need of such an instrument has existed for many years and prior to the adoption of this objective method several subjective means had been applied. The two which were most widely used are described briefly below.

(a) America.†

The method adopted in America is shown diagrammatically in Fig. 1. In this arrangement the communcation circuit was terminated by a network which had an input impedance approximately equal to the characteristic impedance of the line. A telephone receiver formed part of the network. The noise current at the end of the line was compared with the current from a special type of buzzer. The output of the buzzer was applied to the line terminals of a cross-talk meter, and the telephone receiver was connected alternately to the line and meter. The meter setting was varied until the volume of sound heard in the two positions was considered to be the same.

(b) Germany.

In the German method the line noise was compared with the output from an 800-cycle oscillator (see Fig. 2). At this frequency the impedance of the receiver was equal to the characteristic impedance of standard cable. Early methods of noise measurement employed in this country were similar in principle to the above. For example, the characteristic "fry" of carbon granule transmitters was measured by aural comparison with the complex tone produced by an "artificial frying machine"—a light wire carrying current and passing over a rough surface. Again, the arrangement given in Fig. 3 was standardized for determining the relative merits of d.c. generators for telephone purposes.

These methods, however, possessed the following disadvantages:—

(1) An estimation of the loudness of the disturbance was obtained. This is not necessarily a measure of the disturbing effect on telephone conversation.

(2) The results obtained by different observers varied considerably and were influenced by peculiarities of the individual and by local conditions.

(3) Aural comparison of dissimilar noises is very difficult.

In 1926 an extensive series of tests was made by the British Post Office to determine the reduction in articulation efficiency* caused by single-frequency disturbances across the receiver. Meaningless monosyllables were transmitted over the old standard C.B. test circuit (see Fig. 4), and a measured voltage of single-frequency alternating current was impressed across the receiver. The relationship between reduction in articulation efficiency and millivolts of applied alternating current at various frequencies is given by the curves in Fig. 5.

* Comité Consultatif International des Communications Téléphoniques à Grande Distance.

† See Bibliography, (1).

* Articulation efficiency is the percentage of meaningless monosyllables correctly transmitted.

It will be seen that the reduction caused by a certain disturbing voltage depends on the frequency as well as the magnitude of the disturbance and reaches a maximum at about 1 150 cycles. Reference to Fig. 6 will show that these facts can be explained to some extent by the frequency/response characteristic of the receiver used. The sensitivity of the ear to, and the masking effect of, different frequencies also influence the results.

In 1930 similar tests were carried out, but in this

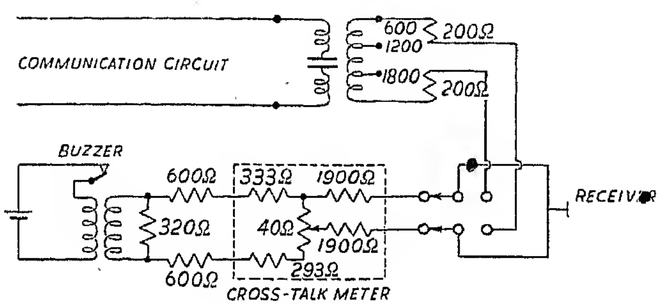


Fig. 1

series the standard cable was replaced by 30 db. of a non-reactive attenuator which had a characteristic impedance (Z_0) of 600 ohms; the disturbing voltage was applied at the centre of the attenuator. The curves in Fig. 7 give the reduction in articulation efficiency produced by various single-frequency disturbances measured across the line terminals of the subscriber's termination. Figs. 5 and 7 should be related to some extent by the attenuation characteristic of the termination which is reproduced in the lowest curve of Fig. 8.

From the curves in Fig. 5 it is possible to derive another curve which will indicate the number of millivolts of a single-frequency alternating current, measured across the receiver terminals, which will cause a 5 % loss in articulation efficiency on the circuit given in Fig. 4, e.g. approximately 0·16 mV of pure tone at 1 150 cycles will produce this loss, whereas at 50 cycles

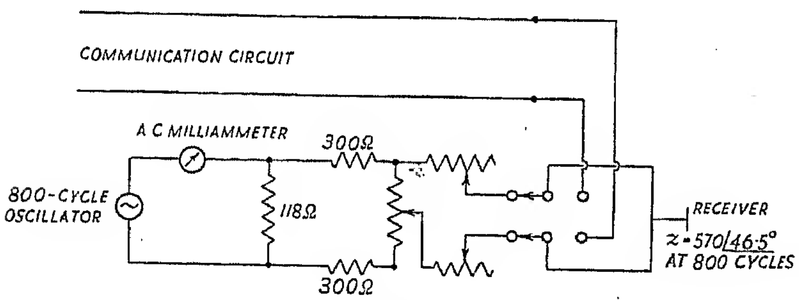


Fig. 2

0·8 mV can be tolerated. The inverse of such a curve will give the relative disturbing effects, referred to a 5 % loss in articulation efficiency, of different frequencies. The inverse curve has been termed a "weighting curve."

A valve voltmeter was constructed which had a frequency characteristic similar to the weighting curve described above, and the output was measured on a thermal instrument, since the r.m.s. law of addition is definite.

A similar series of tests had been carried out in America by H. S. Osborne.* Over 60 000 observations were made, and a weighting curve for a 5 % loss in articulation efficiency was obtained in terms of disturbing current through the receiver associated with a different testing circuit. This curve was more peaky than the one calculated from the British tests but indicated that some frequency weighting was desirable.

In March 1930 a meeting of the C.M.I.* was held at Dollis Hill. During this meeting the delegates made comparative measurements of four different types of

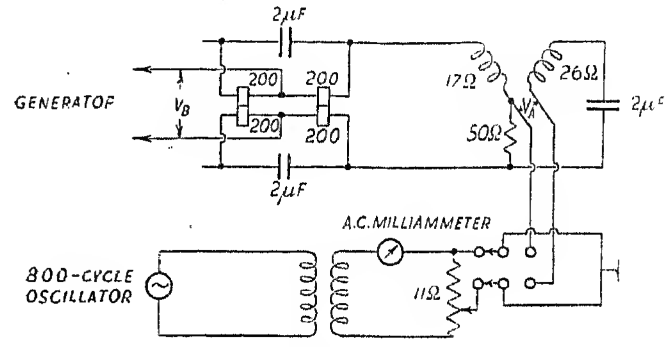


Fig. 3

disturbance by the American, German, and valve voltmeter methods. It was agreed that the valve voltmeter method should be adopted and that the precise specification for the actual instrument should be determined by the C.C.I.F. The original specification has been amended from time to time in the light of experience, and the latest proposals are given below.

(2) SPECIFICATION OF THE PSOPHOMETER, PROPOSED BY C.C.I.F.

Frequency Weighting.

(i) The attenuation/frequency curve of the psophometer must correspond to the values shown in Table 1 and the curves shown in Figs. 87 and 88 of Tome IV of the Livre Blanc of the C.C.I.F., pages 254 and 255, within the limits of tolerance shown by Table 2.

The maximum ordinate of the curve should lie between 1 000 and 1 100 cycles.

(ii) From Table 1 it will be seen that indications of the meter are in terms of an equivalent voltage at 800 cycles per sec.

(iii) It should be so arranged that the amplitude of the low-frequency components is reduced at the earliest stage in the psophometer circuit to such an extent that overloading of the amplifier or other parts of the circuit is safely avoided.

Indicating Instrument.

(iv) The measuring instrument should be so graduated that, when due regard is paid to the setting of the internal potentiometric devices, it reads directly the voltage at 800 cycles per sec. equivalent to the voltage applied to the input terminals.

(v) When the applied voltage consists of a mixture of a number of components at different frequencies, the reading given by the instrument must be equal to the square root of the sum of the squares of the readings corresponding to the individual components, if each existed alone. This power-addition property may be tested by applying simultaneously two well-separated

* See Bibliography, (2).

* Commission Mixte Internationale.

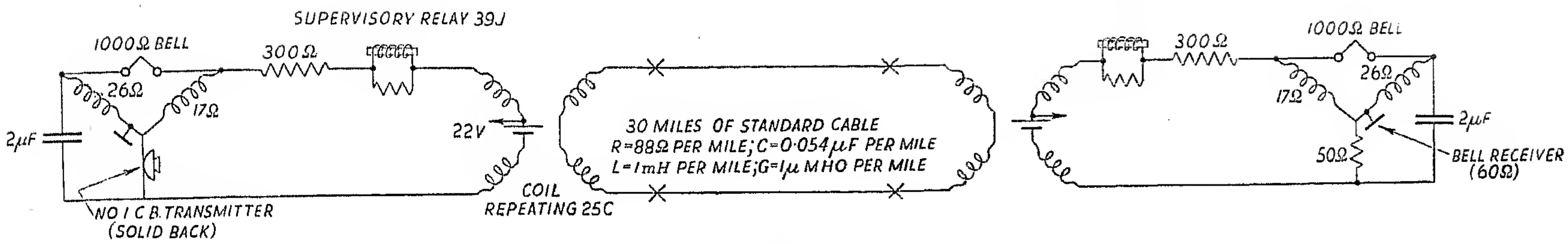


Fig. 4

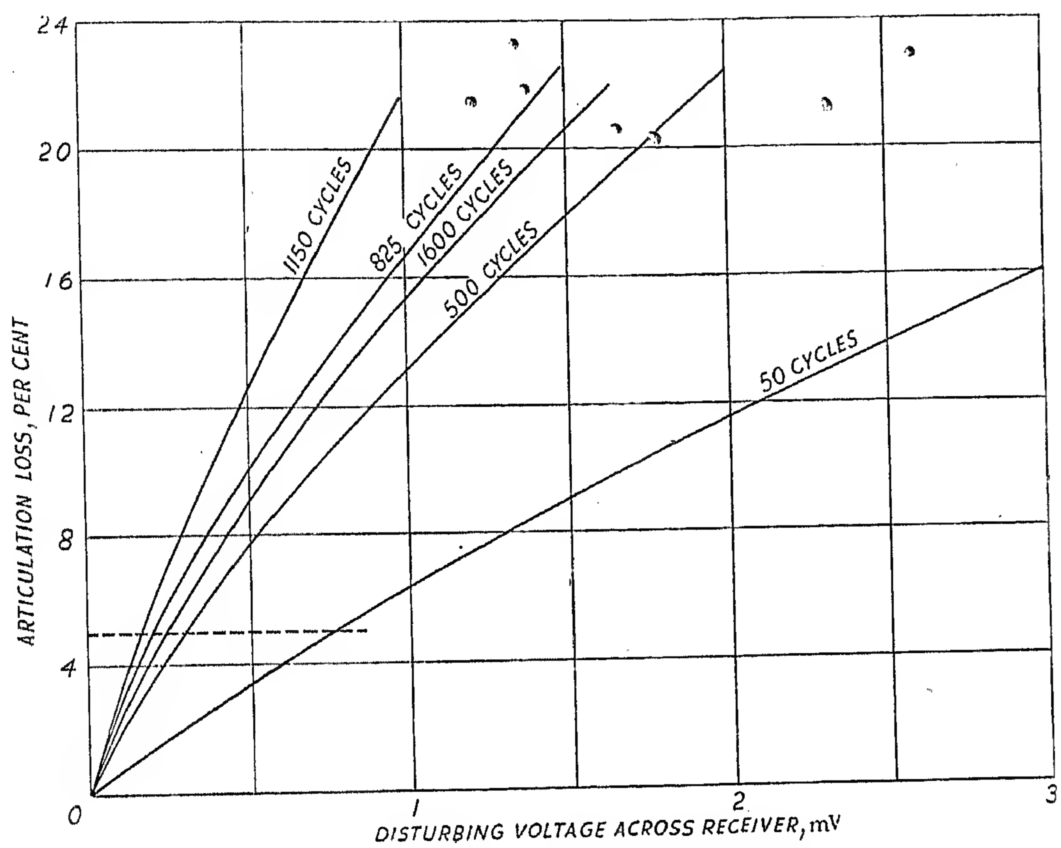


Fig. 5.—Articulation loss due to noise across receiver (Bell).

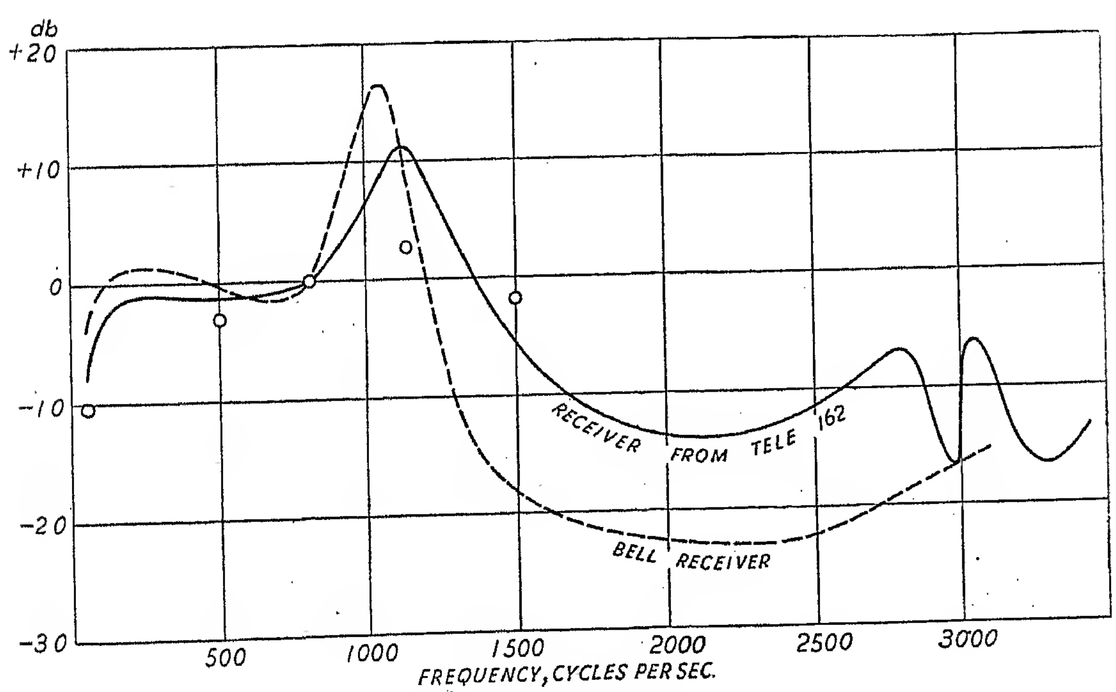


Fig. 6.—Frequency-response characteristic of receivers held to the ear.

○ Relative disturbing voltages to produce 5 % loss in articulation efficiency.

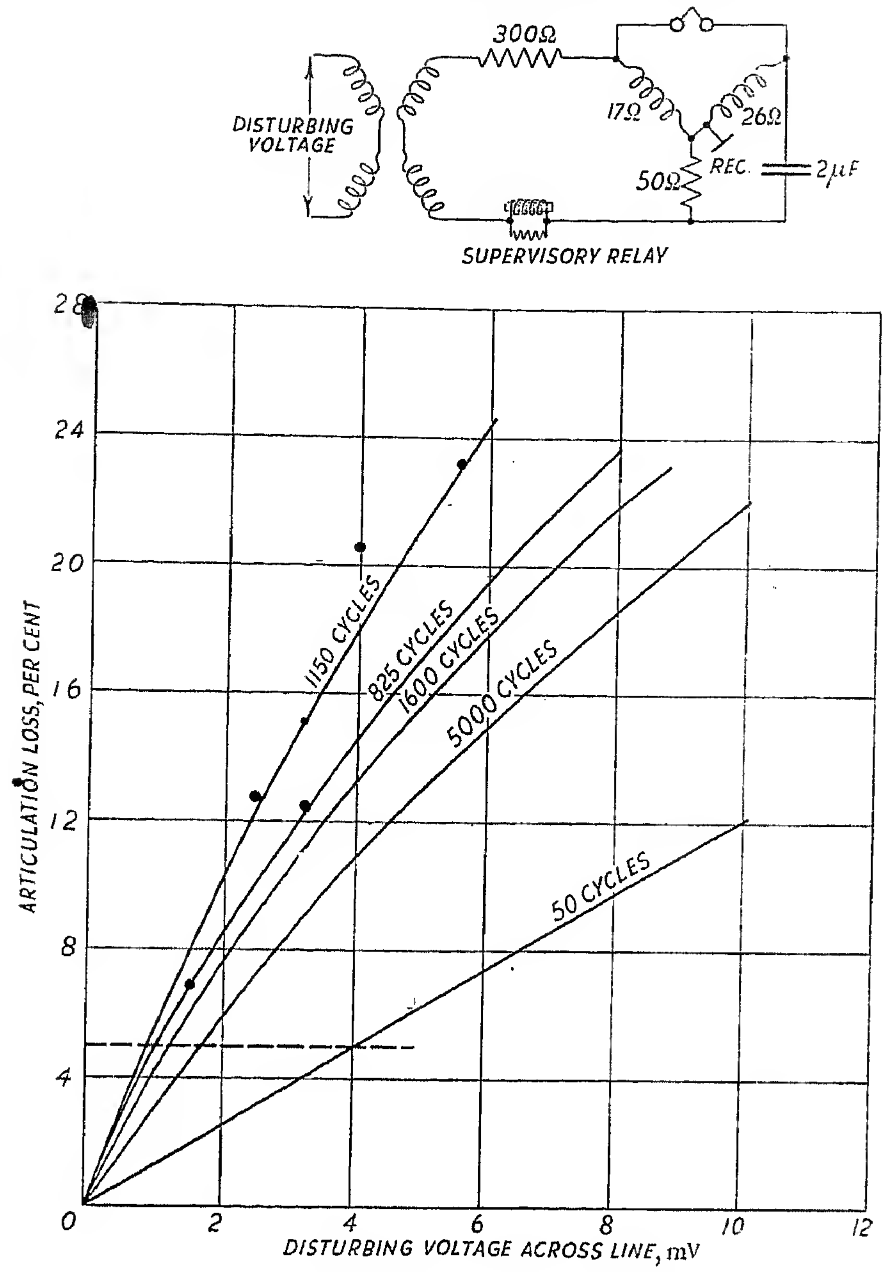


Fig. 7.—Loss in articulation due to noise across line.

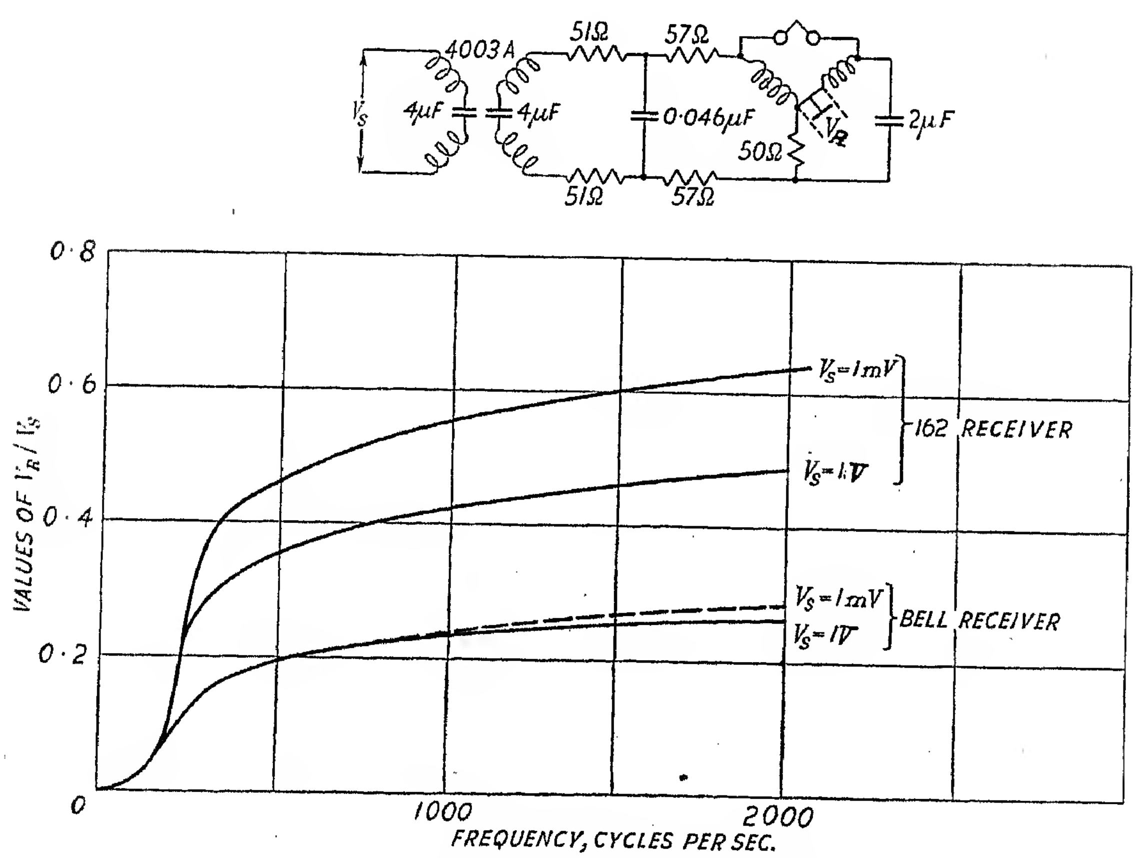


Fig. 8.—Attenuation of C.B. subscriber's circuit.

single-frequency voltages in non-harmonic relation to each other which, when each is measured alone, give the same deflection on the indicating instrument. These are attenuated equally so that they again give this deflection when applied together. The attenuation should be 3 db. with a tolerance of ± 0·5 db.

Table 1

Frequency	Weighting		
	Relative disturbing value*	Decibels	Nepers
cycles per sec.			
16·7	0·115	− 78·8	− 9·07
50	2·48	− 52·1	− 6·00
60	4·1	− 47·7	− 5·50
100	15·0	− 36·5	− 4·20
150	46	− 26·7	− 3·08
180	80	− 21·9	− 2·53
200	105	− 19·6	− 2·25
300	300	− 10·5	− 1·20
400	400	− 8·0	− 0·92
500	472	− 6·5	− 0·75
600	560	− 5·0	− 0·58
700	705	− 3·0	− 0·35
800	1 000	0	0
900	1 405	+ 3·0	+ 0·34
1 000	1 840	+ 5·3	+ 0·61
1 050	1 880	+ 5·5	+ 0·63
1 100	1 770	+ 5·0	+ 0·57
1 200	1 260	+ 2·0	+ 0·23
1 300	795	− 2·0	− 0·23
1 400	527	− 5·6	− 0·64
1 500	419	− 7·6	− 0·87
1 600	353	− 9·0	− 1·04
1 800	289	− 10·8	− 1·24
2 000	254	− 11·9	− 1·37
2 200	225	− 13·0	− 1·49
2 400	200	− 14·0	− 1·61
2 600	177	− 15·0	− 1·73
2 800	159	− 16·0	− 1·84
3 000	141	− 17·0	− 1·96
3 500	80	− 21·9	− 2·53
4 000	45	− 26·9	− 3·10
5 000	19	− 34·4	− 3·96

* The figures given in this column are exact values. The corresponding values of decibels and nepers have been rounded off.

Input Impedance.

(vi) The input impedance of the psophometer should be as great as possible and must in any case be at least equal to 10 000 ohms over the frequency range from 15 to 5 000 cycles per sec.

Sensitivity.

(vii) A clear reading should be given when a voltage not exceeding 0·05 mV at 800 cycles per sec. is applied to the input terminals of the psophometer. The instrument should also permit of direct measurement of voltages up to at least 100 mV at this frequency without the use of external potentiometric devices.

(viii) Over the whole range of the indicating instrument, for every setting of the internal potentiometric device and at any frequency, the reading given by the instrument should be proportional to the magnitude of the applied voltage.

Adjustment.

(ix) Means should be provided whereby the gain of the amplifier may be adjusted to a given value before a series of tests with an error not exceeding ± 5 %.

(x) It will be found convenient if the indicating instrument is capable of being used to check the voltages of the H.T. and L.T. battery supplies, or other means of making this check provided.

Freedom from External Interference.

(xi) The instrument should be entirely unaffected by external magnetic and electric fields. When placed in the most unfavourable direction in a field of 0·05 c.g.s. units alternating at 300 cycles per sec., the reading on the instrument should not exceed 0·05 mV. The psophometer must be screened, as also the boxes containing the batteries, and the various external connections made with screened and twisted pairs. Terminals should be provided for earthing all necessary parts of the apparatus and its cases when in use.

Table 2

Frequency	Permitted deviation*
cycles per sec.	db.
50 to 60	± 2
60 to 150	± 3
150 to 400	± 2
400 to 800	± 1
800	0
800 to 1 800	± 1
1 800 to 3 000	± 3
3 000 to 5 000	± 5

* This is best checked by connecting a variable attenuator, closed by its characteristic resistance, between a source and the psophometer. A sinusoidal voltage input to the attenuator is maintained constant in magnitude but varied in frequency. The setting of the attenuator is varied so that the reading given by the psophometer remains the same for each frequency.

(xii) The symmetry of the psophometer with respect to its case should be such that the application between the input terminals short-circuited together and the case of a potential difference of 200 volts at 50 cycles per sec., or of 30 volts at 300 cycles per sec., or of 10 volts at 800 cycles per sec., does not cause the measuring instrument to give a reading greater than 0·05 mV.

Construction.

(xiii) The operation of the apparatus in field tests shall not be adversely affected by microphonicity or mechanical vibration.

(xiv) The characteristics of the psophometer must be as stable as possible in the practical conditions of use, i.e. in spite of transport, changes of temperature, etc.

(xv) The instrument should be portable and its weight reduced as far as observation of the foregoing conditions permits.

(3) DISCUSSION OF THE SPECIFICATION

Weighting Curve.

The particular weighting prescribed for individual frequencies can give the relative losses in articulation only under very definite conditions of the telephone circuit, its components, and actual observers. It cannot be argued that these conditions are average, but in order to standardize performance some reasonable values had to be fixed. Results obtained in different countries and at different times can now be related and no insurmountable difficulties have been introduced in practice by the adoption of this particular curve as far as the interested parties are concerned. The tolerances allowed are most stringent over the ranges of frequencies which are most prevalent or most important.

In order to reduce the possibility of overloading, it

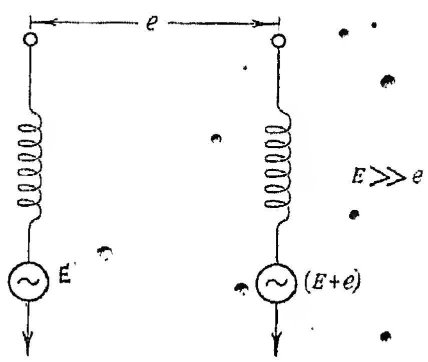


Fig. 9

would appear desirable to specify the tolerance to be allowed on the frequency characteristic of the valve voltmeter.

Indicating Instrument.

The root-mean-square law of addition of the individual components in a complex noise is definite and easily realizable. It is essential that the law should apply for inputs up to four times that required for full-scale deflection, in order to prevent overloading when the ratio of the peak to mean input is considerable. It has been stated elsewhere* that the disturbing effect of a steady complex noise probably has a value between the mean and r.m.s. values of the components.

Freedom from External Interference.

In practice it is sometimes necessary to use the psophometer in confined spaces near to electric power equipment. Reliable measurements would not be possible unless the instrument were practically immune from induction.

When the psophometer is used for measuring the transverse disturbing voltage which exists across the two wires of a telephone pair, it is essential that voltages less than 2 mV can be measured. However, both wires may have a high longitudinal voltage induced into them, as represented in Fig. 9. Hence, it is of vital importance that the input of the psophometer should be carefully balanced to earth.

* See Bibliography, (3).

(4) PRACTICAL MODELS

British Post Office

Two distinct designs of weighting network have been included in Figs. 10 and 11. Apart from the actual shape of the attenuation/frequency curve, there are other factors which limit the design. The attenuation of the network at 800 cycles must be as low as possible. If this were high, extra amplification would be necessary in order to obtain the required sensitivity and protection against external influences would become increasingly difficult. Again, the input impedance of the network should be such as to enable the required input impedance

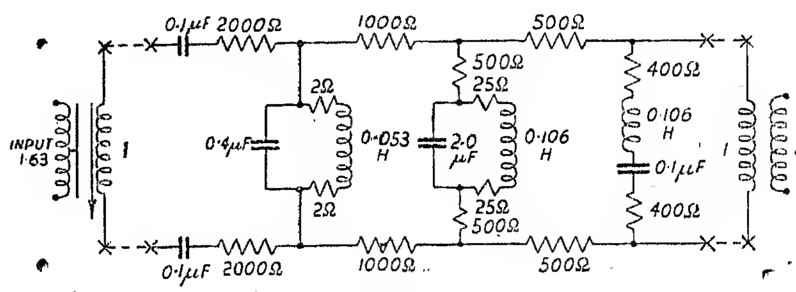


Fig. 10

of the psophometer (> 10 000 ohms) to be more easily realizable.

The attenuation at 800 cycles of the circuit in Fig. 10 is considered too great, but this network has the advantage that comparatively wide adjustments can be made to any tuned circuit without seriously affecting the performance of the others.

The circuit in Fig. 11 is satisfactory from the point of view of attenuation, but its design and adjustment are extremely tedious.

The primary winding of the input transformer must be carefully wound and the two ends must be led out

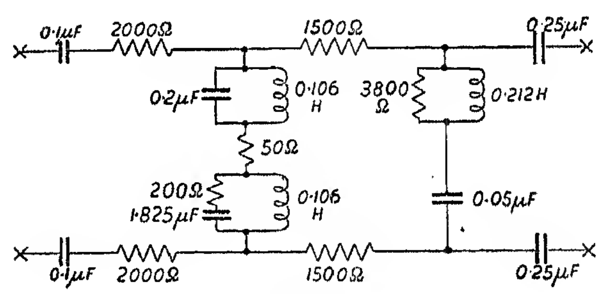


Fig. 11

at different ends of the winding bobbin and on the sides opposite the earth-screened leads to the secondary. In order to secure a sufficiently good balance to earth, the method given in Fig. 12 was adopted. The centre point of the primary winding is connected to an insulated screen. An earthed screen is arranged between this and the secondary winding and completely encloses the latter. In some cases it has been found necessary to include an air-cored inductive resistance between terminals 2 and 5, or 3 and 5.

Low-consumption triode valves were used in the 3-stage resistance-capacity-coupled amplifier. These will probably be replaced by screen-grid or pentode valves. Each stage is separately screened and the first two valves are mounted in non-microphonic holders of the special

design illustrated in Fig. 13. Arrangements are made so that all the valves remain in position during transport.

The rectifier is of the push-pull anode-bend type. The circuit used is given in Fig. 14, and by careful adjustment of the component resistances the amplitude characteristic of Fig. 15 was obtained.

The zero reading of the indicating instrument, which is a d.c. microammeter having a range of 0–100 μA, is adjusted by varying the grid bias of the rectifier valves, when the input to the psophometer is short-circuited.

The input to the psophometer can be reversed so that overloading or dissymmetry can be detected.

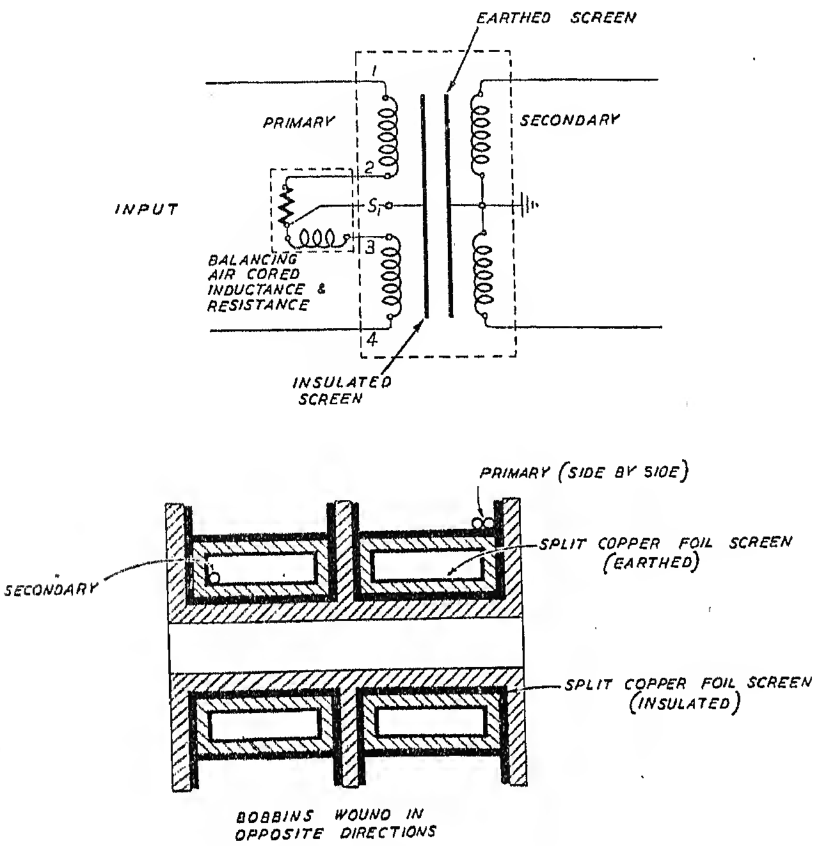


Fig. 12.—Method of balancing screened input transformers.

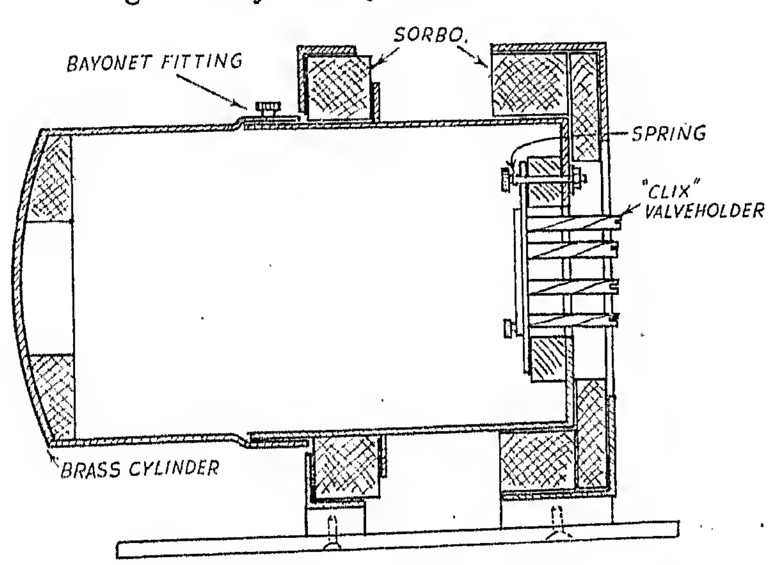


Fig. 13.—Anti-microphonic valveholder.

In addition, facilities are provided for speaking on the test circuit prior to a measurement.

Originally, the sensitivity of the amplifier-rectifier portion only was checked in the field by means of a reed hummer. The calibration of the complete psophometer is now effected by a small portable 800-cycle oscillator which has good frequency stability and small harmonic content.

Batteries are contained in a separate screened box, and connections are made by insulated, twisted, screened leads.

At the request of the C.M.I., one of the earlier models was taken to Faugéres, in order that comparative

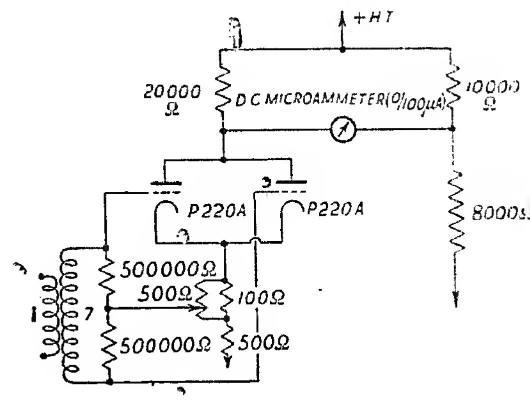


Fig. 14

measurements of the induction from the Midi Railway (which is supplied by mercury-arc rectifiers) to the overhead communication lines of the French Administration could be made. Its performance fully justified this method of noise measurement.

Electrical Research Association

A description of the model psophometer constructed by the British Electrical and Allied Industries Research Association is given in the Association's publication M/T38. This instrument is similar in principle to the one described above. In addition, some variable tuned circuits are included so that the instrument can be used as a harmonic analyser.

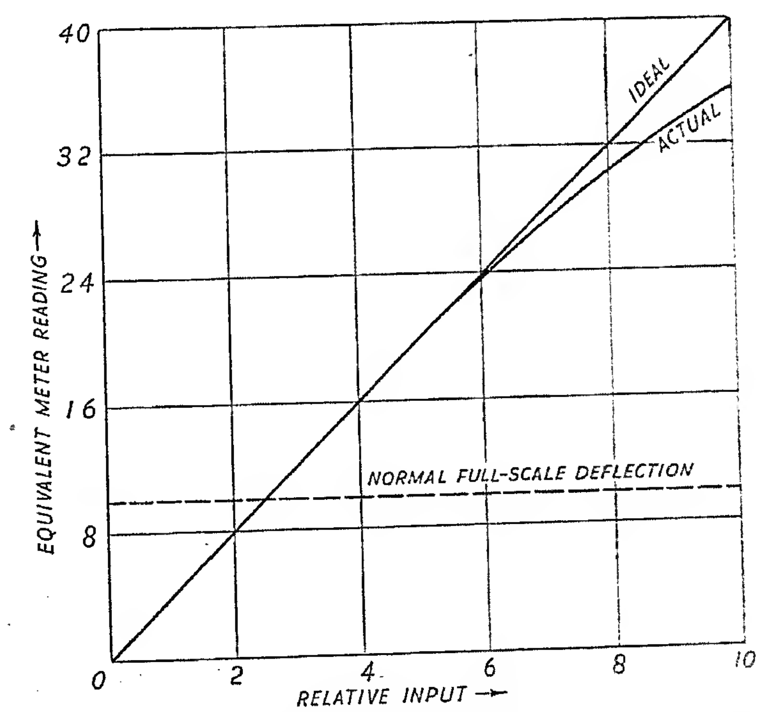


Fig. 15.—Amplitude characteristic of push-pull rectifier.

The first commercial model on similar lines was produced by the General Electric Co. at Coventry last year.

Other psophometers have been constructed by Messrs. Siemens and Halske in Germany; the Swedish Adminis-

tration* and Messrs. Ericsson's† in Sweden; Messrs. Standard Telephones and Cables, Ltd., in England;‡ and the A.T. and T. Co. in America. In these the weighting network follows the first valve and hence, unless this latter is capable of accommodating a comparatively large grid-swing, overloading will occur if large low-frequency components are present in the noise to be measured. The routine calibration of these instruments is effected by a feed-back circuit.

(5) USES OF THE PSOPHOMETER

(a) Transverse Noise Voltage

The psophometer was originally designed for measuring the disturbing effect of power induction in telephone

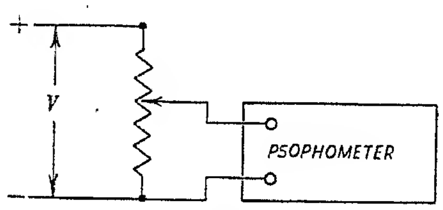


Fig. 16

Psophometer reading $\propto \sqrt{\Sigma(\alpha_f v_f)^2}$, where α_f = weighting factor at frequency f.

circuits. The affected circuit was terminated in a circuit model which consisted of an exchange cord circuit, a subscriber's average line, and instrument. The psophometer was connected across the receiver of the subscriber's instrument. However, the characteristics of the circuit models in different countries are not identical. Hence, in order that similar measurements made in different countries could be compared, it was decided that, until the characteristics of an average termination could be agreed, the psophometer should be connected directly across the ends of the circuit, which should be terminated at both ends by a non-reactive resistance of 600 ohms. The results so obtained give the trans-

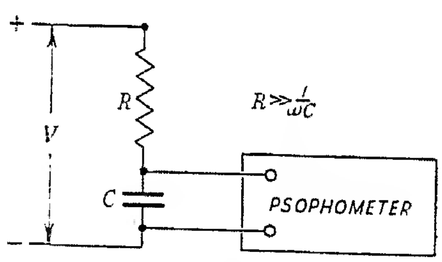


Fig. 17

Psophometer reading $\propto \sqrt{\Sigma\left(\frac{\alpha_f v_f}{\omega CR}\right)^2}$

verse noise p.d., i.e. the millivolts of a pure tone at 800 cycles which will produce the same disturbing effect on telephone conversation as the complex interference.

If the telephone circuit can be assumed to have a characteristic impedance of 600 ohms, then the equivalent noise e.m.f. is double the measured p.d.

The C.C.I.F. has stipulated that the maximum value of this noise e.m.f. shall not exceed (*a*) 5 mV in the case of open-wire circuits, and (*b*) 2 mV in the case of cable circuits.

(b) Longitudinal Noise Voltage

In order to determine the total noise voltage (end to end) induced into a telephone pair, each wire is earthed at the distant end through a 300-ohm non-reactive resistor, and at the near end the wires are joined together and earthed through a resistor of 100 000 ohms. The psophometer is connected across 600 ohms of this resistance at the "earthy" end. No simple relationship exists between the measured transverse voltage and this longitudinal voltage, since the former is affected by unbalance to earth of the telephone pair. However, as a result of a large number of measurements it is hoped that a coefficient of sensitivity will be obtained by means of which the average transverse noise voltage for a given

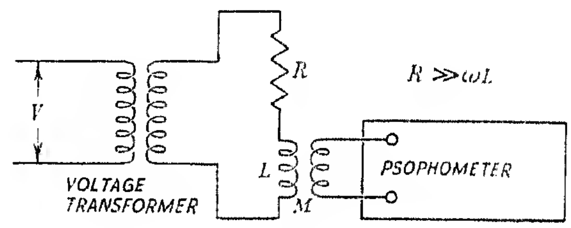


Fig. 18

Psophometer reading $\propto \sqrt{\Sigma\left(\frac{\omega M}{R}\alpha_f v_f\right)^2}$

longitudinal noise voltage can be calculated for overhead and underground communication circuits respectively.

(c) Equivalent Disturbing Current or Voltage of a Power System

It is obviously desirable that measurements made at the source of interference should be related to the disturbance produced. Before the psophometer can be used for these measurements, it is essential that the precise nature of the coupling between the source of interference and the disturbed circuit be ascertained. When the coupling has a simple relationship with frequency the psophometer can be suitably coupled to the source. Methods which have been suggested by the C.C.I.F. are given in Figs. 16, 17, 18, and 19.

Referring to Fig. 19, let i_f be the component of the disturbing current at a frequency f. The current in the

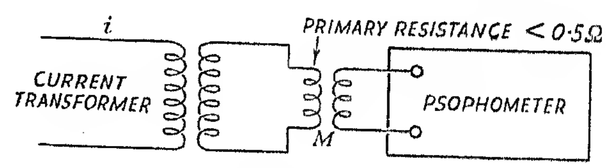


Fig. 19

Psophometer reading $\propto \sqrt{\Sigma(\omega M\alpha_f i_f)^2}$

secondary circuit of the current transformer will be ki_f (approx.). If the psophometer imposes no appreciable load on the secondary of the mutual inductance M, the voltage applied to the instrument will be ωMki_f at the frequency f. This is equivalent to a voltage of $\alpha_f\omega Mki_f$ at a frequency of 800 cycles.

Hence, if the coupling between the source of interference and a disturbed circuit has the characteristics of mutual inductance, then the voltage recorded on the psophometer will be a true measure of the interference which will be experienced, e.g. the longitudinal voltage

* See Bibliography, (4). † *Ibid.*, (5). ‡ *Ibid.*, (6).

induced into a communication circuit is related to the residual earth current due to a power network in this manner.* The circuit of Fig. 19 would appear suitable in this case, although errors may be introduced due to reflections in the power line.

(Note:—The weighting curve of the telephone interference factor meter† was obtained by multiplying the disturbing effect, relative to an equal current through a telephone receiver at a frequency of 800 cycles, of current at any other frequency f by a factor $f/800$.)

Table 3

NOISE E.M.F. FROM D.C. 24-VOLT GENERATORS AT FULL LOAD

Rating	Noise E.M.F.
amp.	mV
75	200
	306
	266
	247
120	283
	124
	264
	82
	264
150	120
	150
	229
	257
	222
	194
200	70
250	66
	118
	188
	188
300	196
	176
	354
	197
	164
	157
600	247

Max. 1·47 %; mean 0·82 %.

(d) Noise E.M.F. from D.C. Supplies

Quite apart from the case of induction from a d.c. power network into communication circuits, it is necessary to determine the noise e.m.f. from d.c. generators and rectifiers which are used for floating the batteries at telephone repeater stations and exchanges. Any noise occurring across these batteries will cause interference with transmission over any circuits which are associated with them.

D.C. Generators.

The internal impedance of a d.c. generator, and the impedance of its associated load, can be determined. It has been found that the impedance of a generator is largely inductive, and a formula for the calculation of its inductance has been derived in Appendix I. Hence, it is possible to measure the noise e.m.f. generated in the machine, at any value of d.c. load, by means of a psophometer connected across the machine terminals.

Table 4

NOISE E.M.F. FROM D.C. 50-VOLT GENERATORS AT FULL LOAD

Rating	Noise E.M.F.
amp.	mV
180	1 250
	1 130
220	344
	328
1 200	533
	730
	604
	604
1 600	137
	270
	380
	375
	230

Max. 2·5 %; mean 1·06 %.

Values which have been obtained at full load for a variety of machines are tabulated in Tables 3, 4, and 5. It will be observed that the average noise e.m.f. generated at full d.c. load is approximately 1 % of the output voltage. The composition of this noise voltage is extremely complex since it contains components at the following frequencies:—*

(a) The fundamental frequency f generated in the armature, and its harmonics, $2f$, $3f$, etc.
(b) The slot-ripple frequency.
(c) The commutator-ripple frequency.

Analyses taken on a particular machine are given in Table 6. Referring to this, it will be seen that the noise e.m.f. increases with d.c. load and that this increase is due largely to the increase in slot ripple.

* See Bibliography, (7) and (8). † *Ibid.*, (2).

* See Bibliography, (9).

Rectifiers.

The rectification of a pure sine wave can be expressed as follows:—

$$y = \frac{m}{\pi} \sin \frac{\pi}{m} \left[1 + 2 \sum_{n=1}^{\infty} \frac{\cos nm\theta}{1 - n^2 m^2} \right]$$

where m is the number of phases. Hence, it would appear that the disturbing effect of the ripples produced by rectifiers could be calculated. However, the magnitude of these ripples is influenced by the type of load to which the rectifier is connected and, in the case of mercury-arc rectifiers, by the ageing of the anodes.

Table 5

NOISE E.M.F. FROM D.C. 130-VOLT GENERATORS AT FULL LOAD

Rating	Noise E.M.F.
amp.	mV
15	400
	850
	1 010
	1 170
	815
	1 180
	1 260
	1 800
	1 040
	2 020
	396
	418
	880
20	1 930
25	4 370
	2 080
40	672
	476
	796
	755
45	374
50	2 760
	1 430

Max. = 3·4 %; mean = 0·97 %.

A psophometer of the type described, or a simpler and less sensitive model, will have an increasing use in this connection.

(e) Permissible Noise Voltage across Batteries

When batteries are floated across rectifiers or d.c. generators, the maximum values which have been specified for noise p.d. across the batteries are as follows:—

(1) *Repeater stations.*

(*a*) 24 V, " A " supply—0·5 mV.

(*b*) 130 V, " B " supply—7 mV.

(2) *Exchanges.*

50 V; — 2 mV.

The limits required under (1) ensure a satisfactory value for the signal-to-noise ratio at the output of repeaters, which are most widely used at the present time, assuming the batteries to be the only source of noise.

Table 6

ANALYSIS OF NOISE E.M.F. FROM D.C. GENERATOR

(*Details of Generator.*—Shunt field; 13/15 A, 175/131 V, 1 500/1 440 r.p.m.; 4 poles; 4 interpoles; 32 skewed slots; wavewound armature; 128 commutator segments.)

No load			Full load		
	Ripple E.M.F.		f	Ripple E.M.F.	
	Direct	Weighted		Direct	Weighted
cycles per sec.	mV	mV	cycles per sec.	mV	mV
50	—	—	48	—	—
100	227	3·4	96	116	1·85
150	73	3·3	144	10	0·41
200	16·7	1·75	192	27	2·43
250	15	3·0	240	7	1·19
300	43	12·9	288	32	8·3
350	16	5·6	336	28	9·5
400	22·7	9·1	384	11·5	4·6
450	4·2	1·83	432	—	—
500	7·5	3·54	480	10·5	4·8
550	5·9	3·04	528	—	—
600	15·5	8·7	576	—	—
650	12·3	7·9	624	—	—
700	5·7	4·0	672	—	—
800	125	125	768	1 750	1 590
1 600	57	20·1	1 536	41·6	14·9
3 200	11	1·21	3 072	54	7·0
R.M.S.		128 mV			1 590 mV
Psophometer reading		140 mV			1 840 mV

It is probable that less stringent conditions will be required for repeaters employing negative feed-back.

Impedance of Batteries.

The actual values of noise p.d. obtained across a battery will be practically proportional to the impedance of the battery circuit, since in most cases the impedance of the load will be considerable.

Measurements on actual batteries have given the values of overall inductance shown in Table 7.

It cannot be emphasized too strongly that any proposed layout of a battery should be considered from the

point of view of minimum inductance consistent with ease of maintenance.

(f) Harmonic Analysis

As has already been indicated, the psophometer can be readily adapted for harmonic analysis. If the weighting network is replaced by suitable tuned circuits, which can be adjusted, a very simple and sensitive harmonic analyser is obtained.

(g) Bridge Detector

It is obvious that the psophometer incorporates the requirements of a sensitive detector for use with a.c. bridges. Balance of the bridge can be ascertained either visually or aurally. In conjunction with the tuned circuits mentioned above, the instrument has been used in bridge measurements of zero phase-sequence impedance of power networks, internal impedance of d.c. generators, internal impedance of rectifiers, etc., under operating conditions.

(h) Interference and Noise Measurements on Multi-channel Carrier Systems

The psophometer is specified for the measurement of inter-channel interference and other noise which occurs on the channels of a multi-channel carrier system.

(6) LIMITATIONS AND FUTURE WORK

The results of tests carried out in different countries and in the same country at different times indicate that the interference with telephone conversation, caused by induction from a.c. power networks into the communication circuit, can be measured by means of a psophometer. The extent of the interference, assessed by loss in articulation efficiency, will depend on the precise conditions obtaining in the circuit. The actual loss in articulation efficiency which will result from a certain amount of mains induction will be affected by the characteristics of the communication circuit and by the presence of other line induction or room noise, side-tone, battery noise, etc., at the receiving end. For example, measurements in this country showed that a 5 % loss in articulation efficiency was produced on the circuit in Fig. 4 by a p.d. across the receiver at the listening end equivalent to 0·16 mV of typical mains induction measured by the psophometer. However, if the 30

Table 7

Battery voltage	Number tested	Inductance (μH)		
		Min.	Max.	Mean
24	22	9·5	32·5	17
50	14	9·75	23	18
130	17	22·5	60	28·5

standard miles of standard cable is replaced by 30 db. of a non-reactive attenuator, the corresponding p.d. is approximately 0·56 mV. This difference is partly explained by the superior frequency response and, hence, higher normal articulation efficiency of the latter circuit.

The arrangement for producing the mains induction used in these tests is shown diagrammatically in Fig. 20.

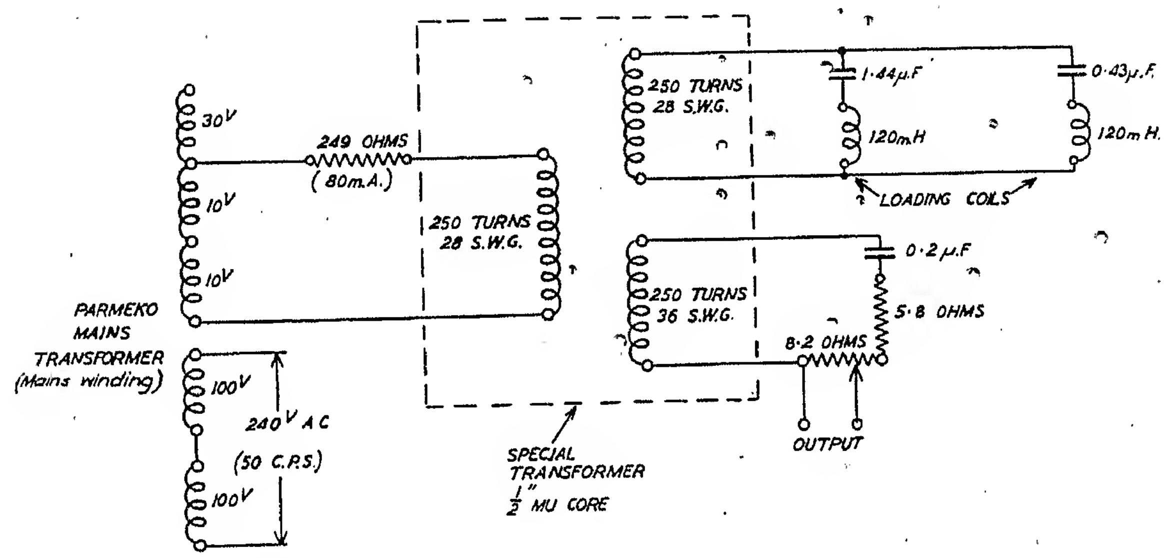


Fig. 20.—Artificial mains-induction noise generator.

Table 8

TYPICAL MAINS INDUCTION

Frequency	Relative magnitude
cycles per sec.	
50	1
150	1·6
250	0·84
350	0·14
450	0·67
550	0·22
Any other component	$<$ 0·056

The relative magnitudes of the harmonics obtained are tabulated in Table 8.

By reference to the curve of Fig. 21, it will be seen that, with the modified circuit, a 5 % loss in articulation efficiency is produced if the attenuation of the junction is increased to 37 db. Thus, the impairment caused by

0·56 mV of mains induction, measured by the psophometer, is 7 db. Now, it has been found in tests recently completed at the Research Station of the British Post Office that the impairment produced by a fixed amount of noise is practically constant above a junction attenuation of 30 db. At the higher values of attenuation, the articulation loss due to this impairment increases. It follows, then, that the interfering effects of noise can be more directly compared on an impairment basis than from loss in articulation efficiency. Another very important factor is that values of impairment obtained from articulation tests are less dependent on the experience of the testing crew.

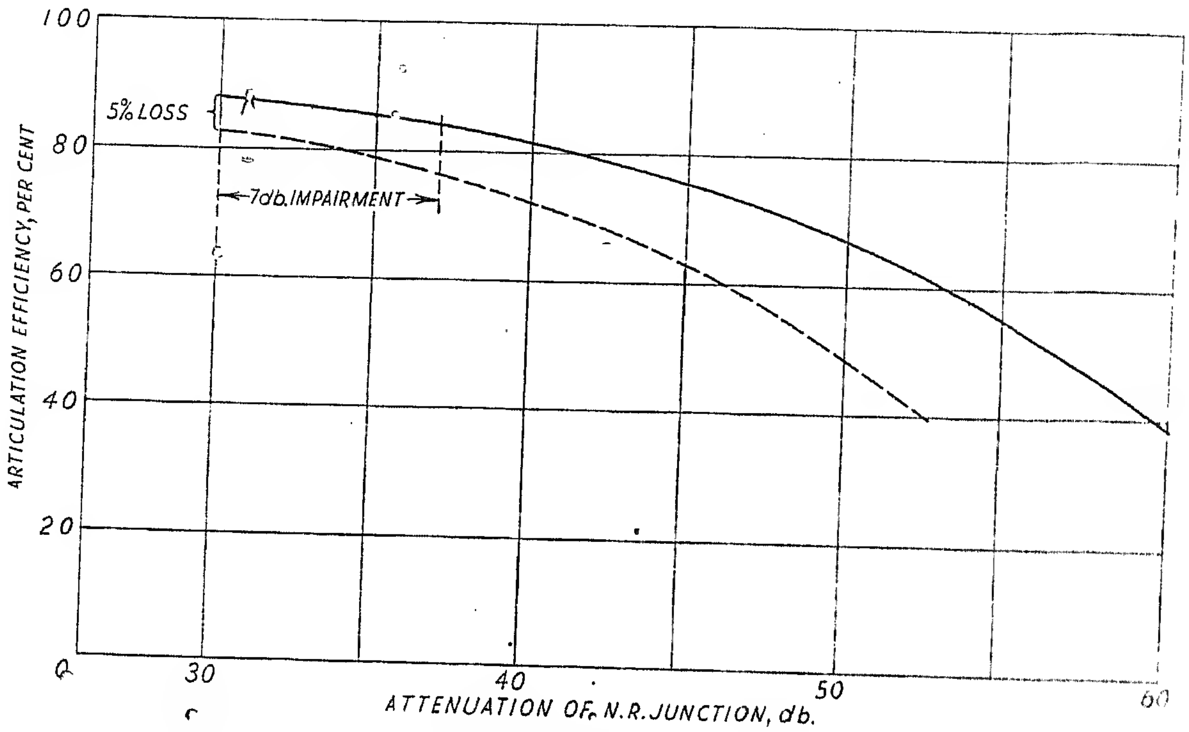


Fig. 21.—Variation of articulation efficiency with junction attenuation.

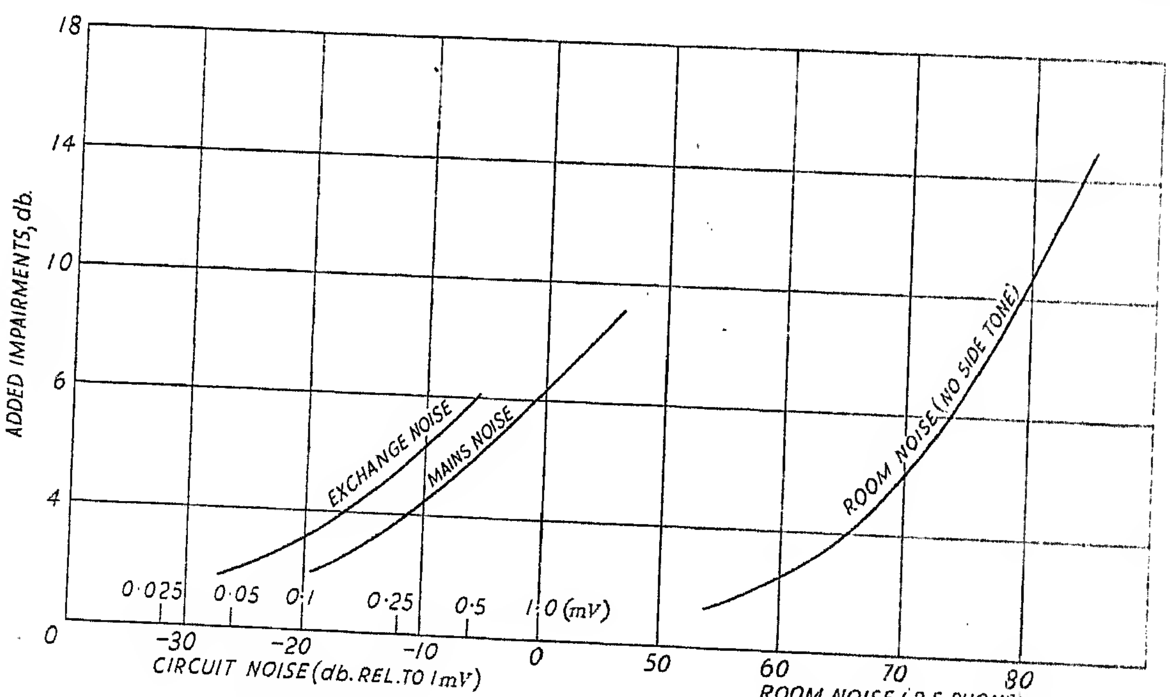


Fig. 22.—Averaged impairments due to a noise in the presence of other noises.

In Fig. 22 the impairments resulting from various amounts of mains induction, room noise, and exchange noise, in the presence of other noise are shown. It will be evident that the impairment resulting from the same voltage, measured by the psophometer, of different types of noise across a telephone receiver depends on the characteristics of the noise. Mains induction can be termed a steady noise, and the masking it produces on speech will be fairly definite. An extensive series of tests in America have confirmed that the psophometer is satisfactory for noises of this type.*

However, the exchange noise used was of a more peaky and intermittent nature, being produced by the artificial frying machine described earlier in the paper. Provided the type of noise to be measured is known, the reading of the psophometer can be related to the interference to be expected.

In practice, induction of the two types sometimes

* See Bibliography, (11)

occurs in the same communication circuit, with the result that a correct estimate of its interference with telephone conversation is exceedingly difficult. In an ideal psophometer no such distinction should be necessary, and the voltage recorded should give a measure of the interference to be expected, irrespective of the type of noise.

Whether or not a comparatively simple instrument such as the present psophometer can replace the complex mechanism of the ear in this connection, is extremely doubtful. Nevertheless, further research is obviously required in order to explore the possibilities of suitable modifications which will render the psophometer satisfactory for a wider range of noises. The initial steps in this direction will certainly be with regard to the indicating instrument, viz. its integrating time and time for decay.

These factors have already been fixed in the instrument which has been adopted for estimating at low frequency the signal/interference ratio from radio receivers.*

Again, a revision of the method of addition of the components in a complex disturbance, and even a modification—possibly a simplification—of the weighting curve, may be necessary.

Lastly, there is a psychological effect which cannot be assessed by an instrument. If an operator or a subscriber knows that noise exists on a particular circuit, the irritation experienced—and this may be unconscious—will tend to reduce the efficiency of his transmission over the circuit.

(7) ACKNOWLEDGMENTS

The author's thanks are due to the Engineer-in-Chief of the Post Office, who granted permission for the paper to be read. In addition, the author desires to express his thanks to the following manufacturers for supplying details of equipment:—Messrs. Austinlite; Messrs. Bruce Peebles; Messrs. Crompton Parkinson; The Electric Construction Co.; The General Electric Co.; and Messrs. Newton Bros.

Finally, the author acknowledges his sincere thanks to Capt. B. S. Cohen, O.B.E., and to all his colleagues, past and present, at the Post Office Engineering Research Station who have so wholeheartedly co-operated in the work described in the paper.

(8) BIBLIOGRAPHY

(1) S. C. Bartholomew: *Post Office Electrical Engineers' Journal*, 1930–31, vol. 23, p. 133.
(2) H. S. Osborne: *Transactions of the American I.E.E.*, 1919, vol. 38, p. 261.
(3) J. Collard: *Post Office Electrical Engineers' Journal*, 1930–31, vol. 23, p. 187.
(4) Report of the Swedish Administration (June, 1935).
(5) *L.M. Ericsson Review*, 1934, No. 3, p. 135.
(6) Catalogue of Physical Society Exhibition, 1937, p. 43.
(7) W. G. Radley and S. Whitehead: *Journal I.E.E.*, 1934, vol. 74, p. 201.
(8) W. G. Radley and H. J. Josephs: *ibid.*, 1937, vol. 80, p. 99.
(9) *Annales des Postes et Telegraphes*, 1933, vol. 22, p. 874.
(10) H. Rissik: *Journal I.E.E.*, 1933, vol. 72, p. 435.
(11) J. M. Barstow, P. W. Blye, and H. E. Kent: *Bell-Monograph*, B. 915.
(12) Report of the International Electrotechnical Commission, C.I.S.P.R., document No. 204.
(13) See also H. M. Hobart: "Electric Motors."

* See Bibliography, (12).

APPENDIX

Inductance of D.C. Generators*

The e.m.f. developed in the armature of a d.c. generator is given by

$$V = \frac{N}{60} Z B_g \pi D l \frac{\gamma}{C} \times 10^{-8}$$

where N = speed of rotation in r.p.m.;
Z = total number of armature conductors;
B_g = flux density in air-gap;
D = diameter of armature in cm.;
l = length of armature in cm.;
$\gamma = \frac{\text{polar arc}}{\text{pole pitch}}$;
and C = number of circuits in parallel between brushes.

Again, the full-load current from a d.c. generator can be shown to be

$$I = \frac{\pi D r_s t f_c}{Z} \Delta \,.\, C$$

where $r_s = \frac{\text{slot width}}{\text{slot pitch}}$
t = depth of slot
$f_c = \frac{\text{net copper per slot}}{\text{slot area}}$ (copper space factor)
Δ = current density in copper.

Hence

$$\frac{V}{I} = \frac{N}{60} Z D l \pi B_g \frac{\gamma}{C} \times 10^{-8} \times \frac{Z}{D \pi r_s t f_c \Delta C}$$
$$= \frac{Nl}{60} Z^2 \frac{B_g \gamma \times 10^{-8}}{r_s t f_c \Delta C^2}$$

or

$$\frac{V}{INl} = \frac{B_g \gamma \times 10^{-8}}{60 r_s t f_c \Delta} \cdot \frac{Z^2}{C^2}$$
$$= \frac{B_g \gamma \times 10^{-8}}{60 r_s t f_c \Delta} T^2$$

where T = number of armature conductors in series.

Now the inductance of the armature (in henrys) is given by

$$L = \frac{\phi T}{I} \times 10^{-8}$$
$$= \frac{\frac{4\pi}{10} T^2}{S} \times 10^{-8}$$

S being the reluctance of the magnetic circuit.

* See Bibliography, (13).

Hence,
$$L = \frac{\frac{4\pi}{10}}{S} \cdot \frac{60 r_s t f_c \Delta}{B_g \gamma} \cdot \frac{V}{INl}$$

But the reluctance of the magnetic path will depend to a very large extent on the reluctance of the interpolar air-space, which is inversely proportional to l.

Therefore
$$L \propto \frac{V}{IN}$$

Now, in a shunt-wound dynamo the inductance of the shunt field will be much greater than that of the armature. Further, the inductance of any interpole or commutating-pole winding will be much less than the armature inductance. It will be seen, therefore, that L can be taken as the inductance of the generator whether connected in long or short shunt.

It would appear, then, that the inductance of a d.c. generator is given by

$$L = \frac{KV}{IN}$$

where K is a constant.

From measurements on a large number of generators, it has been found that the average value of K is $1 \cdot 4$.

[The discussion on this paper will be found on page 275.]

DISCUSSION BEFORE THE METER AND INSTRUMENT SECTION, 4TH FEBRUARY, 1938, ON THE PAPERS BY DR. DAVIS (SEE PAGE 249) AND MR. HARBOTTLE (SEE PAGE 261)

Mr. B. S. Cohen: The title "objective noise-meter" seems to be something of a misnomer. These instruments are just as valuable for the measurement of wanted sounds as of unwanted ones, and perhaps the title used in America—"sound-level meter"—is better than ours.

I consider the two most important requirements in connection with a sound-level meter or objective noise-meter to be, firstly, specifiability and reproducibility; and secondly, the giving of the nearest approximation to subjective results for all the classes of sounds to be measured. I think that Dr. Davis has shown that his meter gives closer results subjectively for various types of noises, and particularly the impulsive types, than other meters. We are, however, never likely to obtain a perfect objective loudness-meter: subjective loudness measurements of the same sound by a number of observers will always cover a wide range. It is in my opinion, therefore, advisable that all these meters should have merely a logarithmic numerical scale, without being labelled in terms of phons. I emphasize this point because the German meter, which is a long way away from subjectivity for impulsive noises, is labelled in phons, and I think that this is likely to cause a great deal of trouble and error in the future. I see no great difficulty in making measurements and legislating for the various sound-levels by specifying the type of noise and the numerical value not to be exceeded on a meter of a specifiable and reproducible type. I think that a little more information from Dr. Davis on the reproducibility would be helpful.

Turning to Mr. Harbottle's paper, this makes no reference to an allied type of instrument used for making equivalent measurements on the power circuits themselves. In America a telephone-interference-factor meter has been devised which makes measurements on the actual power lines and uses a weighting network (Dr. Osborne's curve) which was the prototype of the later circuit noise-meter weighting curves. This instrument also includes a correcting device operating on the assumption that the coupling between the power circuit and the telephone circuit varies directly with the frequency. The weighting network has more recently been modified to represent something very like the C.C.I.F. system described in the paper by Mr. Harbottle. One important difference, however, is the addition of a "B" network to allow for the telephone terminal conditions. The noise value of the power-circuit voltage as measured by the latest American instrument is known as its "telephone influence factor."

The difficulty of introducing the telephone-network effect is that various telephone equivalent networks would be required according to the type of circuit used, but some such network is advisable both in the case of these telephone-interference-factor measurements and also in the case of the psophometer if the results are to be truly comparable with the disturbing effects. All that the C.C.I.F. say is that a meter which is used for making measurements on power circuits should have the C.C.I.F. weighting curve as used in the psophometer, and should in addition have a coupling correcting device designed in accordance with the conditions which may exist. Dr. Whitehead has devised for the E.R.A. a version of this instrument known as the "telephone harmonic factor meter," for making interference measurements on power lines.

It is clear that neither the noise meter nor the circuit-noise meter has yet reached finality in design; and with regard to the circuit-noise meter in particular, it is unfortunate that it is unsuitable for measuring the sort of noises which are produced in the telephone system itself. Nevertheless, Dr. Davis's instrument for measuring air-borne noise, and the circuit noise-meter described by Mr. Harbottle, are most valuable devices for obtaining quantitative results under certain specified conditions, and both of these instruments mark a very definite advance in the art of sound measurement on an engineering basis.

Dr. G. W. C. Kaye: I should first like to recall what I think was a red-letter day in the history of acoustics and the measurement of sound, namely the meeting of the International Acoustics Committee last July in Paris, when some 30 nations reached agreement on questions of acoustical units. Among other things, the "decibel" and the "phon" became international units, the Americans agreeing that the decibel should be confined in future to energy or intensity ratios, and the Germans agreeing that their word "phon" should be restricted to measurements of equivalent loudness. The International Committee further agreed that they would not endorse the claims of any noise-meter which did not attempt to conform to the international phon scale of loudness. The arbitrary specification for a "sound-level meter," which has been used in America and elsewhere, was not supported, therefore, by that body; and it is to be hoped that, as time goes on, the specification will be suitably modified. The same objection applies to the earlier types of German "phon-meters" (to which Mr. Cohen has referred), which work to the former German scale (with a different zero and a different method of listening) but which will no doubt be gradually brought into line with the new international scale.

The International Committee collected the evidence regarding the various noise-meters whch have been produced commercially, and it appeared that, within its limitations, Dr. Davis's meter made considerably the best showing as regards conforming to the international scale of phons. As the Chairman of the Ministry of Transport Noise Committee, I am glad to pay tribute to the excellent service the meter gave in a lengthy investigation of the noises of motor vehicles and motor horns. Over a period of 2–3 years, in which some 50 000 to 60 000 observations were made in all kinds of weather, the meter never failed to give satisfaction both as to accuracy and as to robustness. The meter has also been used on the London tube and surface railways, on aircraft of various kinds, and on air-raid warning devices. A smaller and simplified version has recently been developed by Mr. Fleming at the N.P.L. for the Ministry of Transport.

I might mention that on a visit to America last autumn I was able to examine the state of noise measurement

and noise abatement as compared with our efforts in this country. I came back very reassured, though it was evident that their problems are more acute than ours.

Finally, with regard to Mr. Harbottle's meter, I hope he is not committed too heavily to the term "psophometer"; his other term, "circuit noise-meter," seems to me to be all-sufficing.

Dr. W. S. Tucker: I have been associated with methods for the measurement of noise since they were first introduced, and have watched with interest the progress in the design of instruments employed for this purpose. In the early stages, subjective meters were exclusively employed and gave some encouragement on account of the consistency of the results which were obtained by the early observers. This consistency, however, depended on the nature of the sound. Certain sources of sound, such as aircraft, gave results such that two or more observers were in conflict; and it was considered that the noise had constituents which were separated in the ears of the listeners, and if they failed to concentrate on the same constituent they would give different figures.

The earlier experiments seemed to show that no particular value could be attached to readings below 60 phons, and I doubt whether it would be worth while to attempt to design a meter capable of measuring down to 40 phons in loudness level, especially as a background of 40 phons in the open air is a normal figure for reasonably quiet districts.

The specification given by Dr. Davis requires from the *objective* noise-meter an accuracy greater than that of the average individual human observer. This he can claim to have achieved for continuous sounds. It might be pointed out that noise-meter observations are perpetually fluctuating when made in the open air. Observation of phenomena for a reasonable period enables the eye to select a mean value: the ear experiences similar fluctuations in judgment, but I am of opinion that the mean value cannot be assessed so easily.

The development of the noise meter for impulsive sounds is a more difficult achievement. These impulses may be considered aperiodic, but it is doubtful whether such is actually the case. In the example of a shell burst, the explosion will be found to have originated a heavily-damped train of waves of more or less definite frequency. Wind disturbance also produces impulses, of very low frequency. These seem to be recorded on the noise meter when it is worked in the open air, and are a source of embarrassment to the observer.

It is to be noted that the frequency/sensitivity curves of Fig. 2 stop short at 50 cycles per sec. It is to be assumed that this represents a definite limitation of range of frequencies and therefore no deflections as observed by the instrument are attributable to frequencies below this value. It is recognized that the amplifier ceases to function at very low frequencies, but the microphone is still sensitive. The wind disturbance, therefore, must be attributed to the secondary disturbances produced by wind around objects in the locality.

In surveying the conditions requisite for dealing with impulsive sounds, a suggested procedure is that the objective noise-meter is set from observations obtained from the subjective noise-meter, in which it is required to balance a single impulse against a sound of 1 000 cycles per sec. This operation must be extremely difficult.

The new technique introduced by Dr. Davis, of alternate listening, should be a great advance on that previously employed with subjective meters. In making records, the film has advantages over the gramophone, as it gives a better record of the low-frequency sound. It is not understood, however, how the volume of the loud-speaker can be reproduced as a correct volume, and this point should be cleared up. The reproduction cannot be exact, and it is difficult to say how the disappearance of low frequencies will affect the result.

Dealing with wave-forms of noise, the time marks of $\frac{1}{25}$ sec. do not appear to be correct.

Table 2 of the paper by Dr. Davis shows remarkable consistency between aural observations and those given by the instruments, and establishes the noise meter as a useful device. Figs. 6 and 7 also demonstrate the advantage of alternate listening.

It is believed that a much wider scatter would have been produced for the fainter sounds below 60 phons, and in this region both objective and subjective instruments would be more difficult to use.

In the noise-meters now on the market, it is to be noticed that the condenser microphone is not employed. For field work, where it has to be exposed to changing weather conditions, we have found it extremely troublesome. Unless carefully housed, it loses its calibration. This is at variance with Dr. Davis's statement. I should like to ask him whether he has any objection to the use of the crystal microphone or the electromagnetic type. Both have good response curves and should be capable of adoption for outdoor work.

In conclusion, while the instrument described can obviously deal with most of the sounds which occur in everyday life, it may fail to give a true estimate of large impulses such as those set up by maroons, and low-frequency sounds like the lower notes of aircraft. Some other device also must be employed for assessing backgrounds in quiet localities. These latter measurements are vital in air-raid warnings, where the first indications to the ordinary observers depend on the threshold of listening as given locally.

Dr. S. Whitehead: The instrument described by Mr. Harbottle and the C.C.I.F. Specification which it fulfils are excellent for the purposes of the telephone engineer but not so suited to the power engineer. Whereas the American co-ordinating body has defined a single weighting curve for the "telephone influence factor" of power plant, the C.C.I.F. provides a number of different couplings, according to the particular way in which the interference is transferred from the power system to the telephone circuit. Although these are valuable to the telephone engineer, a unique form of coupling is desirable for the power engineer, since the particular couplings defined are often impossible to foresee at a stage when changes in design could be made which would render them innocuous. Capt. Cohen mentioned that the E.R.A. took a step in this direction by defining the "telephone harmonic factor," which omits the special frequency factor, but this has not so far been accepted in the international field. In addition, there is the further complication that the American basic weighting curve

differs from the C.C.I.F. weighting curve, apart from special factors previously mentioned, although in official publications the two are stated to be the same. The psophometer described in the paper is necessarily fairly expensive. For power use, a much simplified instrument is adequate and it should be possible to avoid amplifying valves, since there is nearly always a voltage of 110 volts, with 50 to 100 VA, available. The sensitivity can be much less than in the C.C.I.F. Specification; from about 500 mV to 5 or 10 equivalent volts at 800 cycles per sec. should cover what is necessary. Such an instrument is in course of development by a member of the E.R.A., and gives good promise. It has no valves, a great advantage in works testing.

Mr. Harbottle's equivalent mains noise seems to give undue prominence to triple harmonics, which, with the use of delta windings on supply transformers and the relative importance of mercury-arc rectifiers, will not in the future be expected to be so noticeable. I should like also to know the relation between the noise limits across batteries and the maximum permissible transverse induced noise. I presume Mr. Harbottle's input transformer is astatic in the sense of the windings being each in two halves oppositely wound on the opposite limbs, an arrangement which I have found very useful in reducing disturbance from external fields. A multivibrator offers advantages as a calibrating source since it is inherently stable and does not require to have a high absolute constancy of frequency.

I am rather surprised that while Mr. Harbottle refers to the work of the C.I.S.P.R., Dr. Davis makes no reference to it—although the form of measurement used by that body is similar to the one he describes. The C.I.S.P.R. have developed a leaking peak voltmeter for assessing the disturbing effect of radio-frequency radiation on wireless reception and communication, having made a number of experiments very similar to those of Dr. Davis. The method developed has been specified in B.S.S. No. 727—1937 and also in certain I.E.C. publications (the R.I. series). The time constants of the meter are 1 millisec. on charge and 160 millisec. on discharge, the needle being critically damped with a constant of 160 millisec. These constants are of similar order to those of the meter due to Dr. Davis, owing to the fact that the C.I.S.P.R. method was designed empirically to meet the kind of noise which Dr. Davis stresses, namely repeated impulsive noises. Although the method has been fairly successful, there still seems some difficulty with chains of transient impulses. For example, with the interference radiated from an automobile ignition system, as the speed of the engine is increased from idling onwards, the reading is first low, corresponding to the integration of a single very rapid impulse. When the interval between successive impulses is less than the discharging time of the meter then it charges up to a value approaching the peak of the individual impulse. With the meter as at present designed, the effect of repetition seems unduly exaggerated as compared with aural measurements in this instance. Has Dr. Davis experienced this difficulty with noises of purely "acoustic" origin? It may be added that the C.I.S.P.R. found that a frequency-correction filter added little to the accuracy of their method as regards the disturbances commonly encountered. Some information, additional to that to be found in the publications quoted, is given on this work in a paper by Gill and Whitehead which will be published in due course in the *Journal.*

Mr. W. West: Differences of opinion concerning noise measurement are to be expected if only because of the differences in type of problem and type of noise which are presented to different individuals or organizations. From my experience of the noise problems encountered by the Engineering Department of the Post Office, it seems to me even more desirable to possess a noise-meter which constitutes a good physical standard than one which has been proved to measure equivalent loudness for certain sounds. What is necessary to standardize an objective noise-meter is the drawing up of an agreed performance specification in terms of physical tests which all meters conforming to the specification should be required to pass.

I notice that Dr. Davis does not mention even the desirability of establishing a specification of this kind, yet surely it should be the chief reason for introducing an objective meter at all into so subjective a technique as noise measurement. I mistrust all uncalibrated meters and feel the need to check the accuracy at will, not only when the meter is purchased, but at any time during its service. This need is not satisfied by the meter described in the paper, because the only mention made of a specification merely throws the onus of calibration back on the ear.

I agree with Mr. Harbottle that the psophometer has done very useful work, but I do not think that the credit should go to the technical merits of the specification so much as to the fact that it has been accepted as a standard by wide international agreement. The demand for a standard is such that the psophometer has been put to many uses for which it was not originally designed or intended—simply because it was the only available objective standard. I submit that a much simpler specification, adopted as a standard, would have been just as useful, and possibly more so.

Some of the difficulties and anomalies due to including frequency-weighting for the receiver in the specification may be enumerated as follows: The calibration is made at a frequency (800 cycles per sec.) where the curve is so steep that a 10 % error in the frequency of the calibrating tone results in a 40 % error in the calibration. The specification, though attainable, is so hard to meet that considerable delays and expense have been experienced in obtaining a reliable instrument. The weighting curve is based on tests using obsolete telephone instruments, and future improvements in telephones will render the shape of the curve still less applicable to service conditions. The justification presented for the weighting curve (Figs. 5 and 7) is not consistent with the weighting used (Table 1)—this indeed is not surprising, because results of subjective tests are not definitely repeatable facts. The weighting is based on considerations of the use of the meter connected across a telephone receiver, but the meter is usually connected at some other point in the circuit.

I would suggest that a standardized circuit noise-meter should have a smooth frequency-characteristic which is substantially flat over the middle frequency-

range and which falls off at the extremities, the rate of falling-off being based only on more permanent considerations than the performance of a telephone receiver, such as the sensitivity of normal hearing and the relative importance of different frequencies to the understanding of speech. For special purposes special networks could be added, if required, as additional apparatus with separate specification and associated terminology.

Mr. C. A. Mason: I shall confine my remarks to the paper by Dr. Davis.

There seem to be three main problems in the design of an objective noise-meter. The first is to make the free-field frequency/response characteristic of the meter the same as that of the ear; the second is to make sure that the meter gives the same indication on impulsive as on other types of noise (this point is concerned with the design of the output meter); and the third is that the instrument should give correct indications irrespective of the constitution and relative magnitudes of the components in the noise.

Referring to the first problem, I notice from Fig. 2 that there is some divergence between the free-field response characteristic of the instrument described and the characteristics of the ear obtained by Fletcher and Munson. These characteristics have now been measured by Churcher and King in this country under true free-space conditions, and these are the ones which I should like to see used at the present time.

The Acoustical Society of America have issued definite recommendations as to which frequency/response curve should be used, and we have built instruments in this country to their specification. These have been used to check certain classes of apparatus which have been imported from America, and have given readings of loudness level which have agreed within 1 db. with the values obtained on American instruments in the United States.

I would support the desire which has been expressed by Mr. West that a physical specification should be issued for the objective noise-meter, in order to increase its usefulness.

There is one other point to which I would like to refer in connection with frequency calibration, and that is the use of the condenser microphone. This type of microphone has a bad characteristic; and also shows considerable variation in response according to the direction from which the sound wave arrives. I am surprised that the author should correct it in such a simple manner as the one he describes. We have used the multi-cell type of piezo-electric microphone; what has been his experience with this type?

Referring to the third problem in the design of objective noise-meters, it has been noticed in the past that where noise (e.g. transformer noise) consists of a number of components of about the same intensity level, the readings given by an objective meter are considerably lower than those obtained by subjective measurement, and it occurs to me that perhaps some of the discrepancies mentioned in the paper were due not to impulsiveness of the noise but to its particular constitution.

In connection with the minimum audible sound which can be measured by objective noise-meters, I should like to say that using the multi-cell type of piezo-electric microphone it is possible to measure down to about 25 phons, the limitation being not in the microphone but in the amount of noise which arrives from the first amplifier stage. If a dynamic microphone were used we could get down to about 10 phons, but unfortunately for our particular problems—the measurement of the noise of electrical machinery—the dynamic microphone would pick up by magnetic induction far greater signals than it does acoustically, and we have therefore had no experience with it. I should like to have the opinion of the author as to whether the lower limit to which he can measure is due to his microphone or to noise limitations in his amplifier.

Mr. Donald McMillan: I propose to confine my remarks to the paper by Dr. Davis.

I have made a number of measurements of room noise, using an instrument of the type which he describes, and also one which complies with the American specification. In our investigation 17 different types of room noise were measured, both subjectively and objectively, and about 100 measurements were made. The noises included some which were impulsive in nature (one consisting of a series of blows at about 6 per sec.). A statistical survey of the results leads me to believe that all the differences between the objective and subjective readings are distributed very nearly according to a normal error law; that is to say, they occur entirely at random, and I can trace no definite connection between the type of noise and the discrepancy between the objective and the subjective results. The impulsive type of noise, 6 blows per sec., gave the same reading on the N.P.L.-type meter as on the American-type meter. Each meter seemed to require a small correction, which was of the order of 2 for the N.P.L. meter and 7 for the American meter, in order to bring the objective readings most nearly into line with the subjective results. I therefore agree with the author that the N.P.L. meter does measure, on the average, true phons, but I cannot agree with him, at the moment at any rate, when he says that the American instrument is much inferior to it when dealing with impulsive noises.

We had great difficulty in making our subjective measurements. The Post Office are interested almost solely in room noises which cannot be measured by the technique of the phon as specified, because the technique necessitates alternate listening and free-space conditions. We therefore had to have recourse to a calibrated audiometer of the Barkhausen type and of necessity to listen to the two noises simultaneously. This may have introduced some errors, but I still cannot understand the differences of 20 or 30 phons which the author mentions as existing between the readings of the two types of objective meter. We found no such large discrepancy with any type of noise.

I do not believe that we should have been justified in reproducing the noise to be tested in the manner described by Dr. Davis. An observer's impression of a noise seems to depend upon his surroundings, and I think that it should be fundamental that room noises must be observed in the rooms in which they occur. In any case, it is not practicable to reproduce room noises for the purpose of measuring their loudness (which is the quantity required to be known in practice). The adjustment

of the proper level of reproduction seems to present very considerable difficulties.

On page 253 the author says that several of the sounds to be measured were reproduced at the correct volume by means of a loud-speaker. I should be interested to know how the volume was measured. Further, does he expect an error to occur due to the use of a loud-speaker to reproduce impulsive noises? Presumably the loud-speaker had frequency-characteristic limitations and also a definite type of distribution pattern for the sound in front of it.

Mr. E. Fennessy: The objective noise-meter and the psophometer have much in common; the main difference lies in the characteristic of the weighting networks. The psophometer weighting is based upon the relative values of the noise at different frequencies to produce 5 % articulation reduction, while the objective noise-meter weighting is based on the equal-loudness curves. Acoustic engineers might take a lead from telephone engineers, and measure in terms of the reaction that noise produces on us.

The C.C.I.F., in addition to giving the characteristics of a telephone weighting curve, also give a similar curve for noise measurements on broadcast circuits. It will be noted from Table 1 of Mr. Harbottle's paper that for 800 cycles per sec. the telephone-circuit weighting factor is zero. A similar value would be expected for 800 cycles per sec. on the broadcast curve, but for some strange reason it appears in all official documents of the C.C.I.F. as —1 db. Can Mr. Harbottle explain this discrepancy?

He draws attention to the danger of placing the weighting network after the first valve of the valve voltmeter. He fears that overloading of this valve may occur if the noise under measurement consists of a very low frequency and a 1 000-cycle frequency simultaneously. It will be noted from Table 1 of Mr. Harbottle's paper that the weighting for 16 cycles per sec. is $-78\cdot 8$ db., while for 1 000 cycles per sec. it is $+5\cdot 3$ db. Now supposing the noise consists of two frequencies, 16 and 1 000 cycles per sec., for equal indications of the output meter of the psophometer the 16-cycle tone must be $78\cdot 8 + 5\cdot 3 = 84\cdot 1$ db. above the 1 000-cycle tone. I agree that this is a great difference in level, but I can assure Mr. Harbottle that it can be safely dealt with by a suitable triode. To check this I made some tests upon a psophometer produced by Standard Telephones and Cables, Ltd.; no overloading occurred when an input 85 db. above that required for mid-scale deflection of the output meter was applied.

In making measurements of the characteristic of the weighting network, it is necessary to take precautions to ensure that the output from the test oscillator is pure in wave-form and free not only from harmonics but from noise. I should be interested to learn of the precautions Mr. Harbottle took in this respect. In making similar measurements I found it essential to develop an octave filter, which incidentally has proved most useful for noise-analysis work in conjunction with the psophometer.

Mr. Harbottle speaks of the many uses of the psophometer. An application with which I have been associated is the use of the instrument for measurements of noise on circuits intended for open-wire carrier telephony. It is often essential that information giving the expected noise on any particular carrier channel shall be available when the system is being planned. For this purpose a unit called a channel selector has been developed; this unit reduces any 3-kc. band of frequencies between 3 kc. and 35 kc. to the frequency range 0–3 kc., the noise within this band being measured by means of the psophometer.

Dr. W. G. Radley: Methods of coupling the circuit noise-meter to a power circuit were specified by the C.M.I.* to reproduce on a works test-bed the conditions under which it is anticipated that the machine under investigation will affect telephone lines in practice. The nature of the circuit to which the machine will be connected is taken into consideration. Fig. 16, for example, is the method of connection adopted for measurements on convertors, rectifiers, etc., supplying d.c. railways causing induction into open-wire telephone lines; Fig. 17 is the appropriate connection when the latter circuits are in cable. When interference by way of the electric field of a line is feared, Fig. 18 shows the correct connection for the circuit noise-meter on the test-bed. Fig. 19 applies when residual currents cause interference between open-wire power and communication circuits. Such methods are far too complicated as a basis for the general specification of the wave-form of electrical machinery.

I should like to put in a plea for a specification based on circuit noise-meter measurements, but using a standardized simplified coupling. In practice the problem is far more complicated than is even suggested by the four alternative couplings shown by Figs. 16 to 19. Down the line the relative proportions of the harmonics are totally different from what they are at the source, owing to reflection and propagation effects. It becomes, then, quite impossible to calculate the induced noise directly and accurately from the equivalent disturbing voltage of the source. We have, however, in the circuit noise-meter an instrument which not only successfully measures the noise arising from power induction but a means of specifying, crudely perhaps, the deformation of wave-form of electrical machinery from the point of view of its effect on telephone circuits.

I was associated with the experiments using the circuit noise-meter in the South of France to which Mr. Harbottle refers. We were endeavouring to measure a fairly small noise-voltage between two conductors both of which were at a very much higher voltage to earth. The balance of the circuit noise-meter to earth was therefore important, and the Post Office instrument compared very favourably with others in this respect.

Mr. E. L. E. Pawley: There are one or two points in the paper by Dr. Davis on which I should like some further explanation.

His paper is primarily concerned with noise as a nuisance in itself, whereas in telephony and in broadcasting we are more concerned with noise as interference with something else. He has chosen for his meter loudnesses of the order of 90 phons and 65 phons, and it would be interesting, since the same fundamental principles are applicable to sounds of much smaller loudness, if he could

* Commission mixte internationale pour les expériences relatives à la protection des lignes de télécommunication.

extend the range of the meter to sounds of the order of 30 phons. When he does so, however, I am afraid that he will meet with some difficulties, because the curves of aural sensitivity become steeper as the level decreases, and when two simultaneous tones of different frequencies and different levels are being measured there is the question of which curve we shall choose. Further investigation is necessary to determine to what extent the sensitivity of the ear at one frequency is affected by the presence of a sound at another frequency.

In the experiments made by the C.I.S.P.R. in Berlin in 1934, we found that the presence of a weighting network made very little difference to the results of measurements on highly impulsive sounds, and this is confirmed by the author's measurements. I suppose the reason for that is that a finite impulse, even if it be a perfect sinusoid, can be analysed into a number of frequencies covering the whole spectrum, and therefore the weighting factor does not have anything like the effect which it has with a continuous noise.

Can the author state the exact time-constants of his meter, for comparison with those of the meter adopted by the C.I.S.P.R.? It would be interesting to know the charging and discharging times of his circuit and the time-constant of the measuring instrument itself.

He refers to the difference noticed between the measurements of impulsive compressions and impulsive rarefactions. To get over the difficulty caused by this difference has he tried using a perfectly symmetrical circuit for his meter? By using two diodes arranged in push-pull as the rectifying system it is possible to arrange that no differences occur between the readings for the two directions of an impulse. The International Broadcasting Union uses a device of this kind in its peak programme meter.

Dr. L. E. C. Hughes: Does Dr. Davis distinguish between the radial and reverberant responses of the microphone? In my experience there is considerable divergence. Also the condenser microphone, as used, is capable of maintaining its calibration over long periods only if carefully handled. Is the author contemplating changing the microphone to a more robust device, such as a moving-coil microphone similar to the moving-coil receiver used in the C.C.I.F. transmission reference system?

A free grid is not usual in amplifying apparatus; is this likely to affect the calibration when the rectifying valve is changed? It is frequently stated that the effective noise of a given series of components is greater when these are in harmonic relation than when they are somewhat out of harmonic relation; has the author any suggestions as to how this effect may be incorporated in a noise-meter?

The early effort of Dr. Kaye, Dr. Davis, and their colleagues of the B.S.I. Committee on Acoustical Terms, has done much to put this country in the forefront of noise measurements, with the result that their recommendations have been adopted internationally. In the psophometer, it is presumed that since the weighting networks are sanctioned by the C.C.I.F., these would not be changed until that body had been satisfied that the ear has some characteristics which differ from Fletcher and Munson's curves.

Messrs. A. J. King and B. G. Churcher (*communicated*): We shall confine our remarks to the paper by Dr. Davis.

The performance of the conventional objective noise-meter, i.e. a microphone-amplifier–weighting network-rectifier instrument combination, was dealt with in a recent paper* for the case of steady sounds in terms of the B.S.I. standard, the phon. It was shown there, and subsequent experience confirms it, that the standard technique of the phon definition permits a sound lasting 0·5 sec. or longer to be measured, using 10 observers, with a probable error of less than 1 phon. It was also shown that the conventional objective noise-meter may read as much as 25 phons low, depending on the level of the noise and the number of important components present in it. The author has sought to devise an objective noise-meter which will have less error than the conventional type, especially for sounds of short duration. To do this he has modified the output circuit of the conventional meter, making it a "nearly peak" meter, and has adjusted the time-constant of his instrument until he feels that the meter responds to "impulsive" and "intermittent" sounds in the same way as the human ear. This was the method adopted by the Experts Committee of the I.E.C. at the meeting in Berlin in January, 1935, to fix an international basis for the measurement of radio interference. It has since been incorporated in the British Standard interference-measuring set, described in B.S.S. No. 727 (published in March, 1937).

The author anticipates that his meter will read correctly in phons for a wide variety of noises, both sustained and "intermittent." There are two reasons why it is not to be expected that such a "nearly peak" meter would read correctly in phons for all types and levels of noise.

The first concerns the difference between the laws of summation of the human ear at medium and high intensities. It has been shown† that, for multi-component noises at high intensities, a summation of the "equivalent energies" of the components (i.e. energies of equally loud 1 000-cycle tones) is correct, but at medium intensities such a procedure gives a result far too low. In some cases at medium intensities a peak meter would help by increasing the reading, but when tested on the same noises increased by, say, 40 db. the meter could not but read higher than the phon value as the noises would then be in the range where equivalent energy would be the determining factor. It therefore follows that a peak meter cannot read correctly at both medium and high intensities.

The second reason is supplied by the well-known fact that the relative phases of the components of a noise do not affect its loudness, except possibly at extremely high levels, whereas they can modify profoundly its indication on a peak meter. This point has been checked experimentally by listening to a harmonic noise of six components, very like one of the author's "intermittent" noises, and at the same time observing the wave-form of the amplified output of a microphone while varying the relative phase of the components. Although the

* B. G. Churcher and A. J. King: "The Performance of Noise Meters in Terms of the Primary Standard," *Journal I.E.E.*, 1937, vol. 81, p. 57.
† B. G. Churcher and A. J. King: *loc. cit.*

absolute phasing of the sound pressure wave was not known yet it could be demonstrated that large changes in wave-shape, and therefore peak value, did not produce any detectable change in loudness of the noise. Confirmatory evidence is also provided by the fact that the errors of the conventional objective noise-meter determined in the paper referred to above were the same whether the components of a noise were harmonic or non-harmonic, and therefore covered a large range of peak values. In connection with the measurement of the peak value it is well to bear in mind the phase distortion at low frequencies inseparable from any practicable amplifier. The shape of the voltage wave at the input of the peak meter may be entirely different from that of the sound pressure wave at the microphone or that entering the listener's ear.

The next point concerns the use of the word "intermittent" as applied to sounds of short duration but in which all components are tones which are within the audible range. Noises (3) and (4) on page 253 are examples where the components are all harmonics of their respective fundamentals, 25 and 50 cycles per sec. These noises are almost the same as some of those studied in the paper referred to above.

It is stated on page 250 that the pure-tone equal-loudness contours used for adjusting the pure-tone response of the meter are those of Fletcher and Munson, and that they apply to free-space listening conditions. Reference to the original paper of Fletcher and Munson shows that they were obtained by telephones calibrated in a free field at 10 and 60 phons. The two calibrations differed somewhat: that at the higher level was taken, as being thought to be more reliable, and was assumed to hold at all levels. Our subsequent experience has confirmed the reality of the discrepancy, which is due to a non-linear effect associated with telephone listening conditions. Values determined directly in the free field were given in the paper referred to previously. It would have been a wise precaution to have included, among those noises in respect of which the author's meter was checked, a few pure tones at typical frequencies.

For loud, steady noises of over 80 phons it has been shown* that the conventional meter, correctly weighted, has an error usually less than 5 phons. Advantage has been taken of this to develop a really portable objective noise-meter just for loud noises lasting $0 \cdot 5$ sec. or longer. The meter,† which has two ranges, 80–105 and 100–125 phons, is self-contained as regards microphone and batteries and is carried in an attaché case. It measures $12\frac{1}{2}$ in. $\times$ $3\frac{1}{4}$ in. $\times$ 9 in., and weighs 17 lb. A solution to the problem of adhering as closely as possible to the standard phon technique on a noise which cannot be interrupted, is given by the two-telephone subjective noise-meter‡ mentioned by the author at the foot of page 257. The non-linear effect associated with telephone listening conditions, mentioned above, is just detectable in the calibration of this instrument against a 1 000-cycle free field. That the effect is small in this case is attributed to the use of 800 cycles per sec. as the frequency of the reference tone in the telephones, this frequency being one at which the effect is thought to be a minimum.

* B. G. Churcher and A. J. King: *loc. cit.*
† An example was demonstrated at the meeting.
‡ *Nature*, 1936, vol. 138, p. 329.

The present paper is characterized by a certain hesitancy to make definite statements and a tendency to give the author's conclusion from experimental investigations of certain contributory points, without providing the reader with an opportunity to study the results in detail and so check the legitimacy of the conclusions.

The practice of giving the spread of subjective results is to be deprecated as it is useless statistically and, being a matter of chance, may give a totally wrong impression to the reader. The standard deviation of the judgments about their mean, and the probable error of the mean, are much to be preferred. In the same way the error of any one observer cannot be taken as representative of the error of the subjective method of measurement. It is an essential part of this method of measurement that there should be an adequate number of observers, preferably at least 9. It should be realized that the mean group judgment is the significant result of the subjective measurement and a far more definite and stable quantity than an individual judgment. It is therefore the criterion to take in critically appraising the performance of a noise meter. In general, there are several other sources of error and precautions on which quantitative information would need to be forthcoming before any opinion could be formed as to the limits of error of the author's basic measurements. A thorough treatment of the basic standard is an essential preliminary to the critical appraisement of the performance of, and hence the development of, noise meters of any type. This is particularly the case with the basic measurement, in phons, of noises of short duration.

Mr. A. C. Timmis (*communicated*): The calibration of the psophometer enables it to indicate, at least with reasonable approximation, the effect of noise on articulation. But the general effect of power induction on a telephone user is twofold: (1) noticeability, (2) reduction of articulation. Some judgment tests which were made at the Post Office Research Station showed that steady tones having a frequency of 800 cycles per sec. or more and giving a psophometric voltage of 1 millivolt across the receiver of the Post Office handset, were noticeable to the extent that the telephone user would be inclined to complain, quite apart from any effect on the reception of speech. Lower frequencies, however, such as 400 cycles per sec., were more noticeable for the same psophometric voltage. Thus it appears that the weighting curve of the psophometer corresponds fairly well to the noticeability of single tones above 800 cycles per sec. but it does not apply for lower frequencies, and in fixing tolerable noise-limits the reading of the psophometer would not be sufficient by itself. A factor which takes account of the greater noticeability of the lower frequencies should be included.

The author mentions that the psophometer has been specified for measuring unsteady noises such as the interference due to cross-modulation in carrier systems. The instrument was not designed for this purpose, but it will give a reasonable result provided the interference has the rhythm of speech. The original volume indicator, the pointer instrument of which reaches 90 % of its final reading in 200 millisec., gives a good measure of the loudness of speech or noise of a similar type. The instrument used in the British psophometer happens to

have a similar periodic time and this makes it suitable for use in connection with carrier interference and ordinary cross-talk. This characteristic is not included in the C.C.I.F. specification of the psophometer because it is intended only for steady power induction, but a pointer instrument having " volume indicator " characteristics is used in the American and German psophometers.

THE AUTHORS' REPLIES TO THE DISCUSSION

Dr. A. H. Davis (*in reply*): I may perhaps commence by thanking Dr. Kaye for his tribute, as chairman of the Ministry of Transport's Noise Committee, to the field performance of the meter over the period of 2–3 years during which it was employed on investigations of vehicle noise.

I should next like to deal with a few general points concerning the title of the paper. Mr. Cohen considers the term " objective noise-meter " to be something of a misnomer, and prefers the term " sound-level meter " used in America. The term which I have used is, of course, that adopted by the British Standards Institution. It seems to me that even if that Institution had desired to use the term " sound-level meter " for such an instrument, they could not have done so in present circumstances. For the term " sound-level meter " has obtained a considerable vogue in connection with a meter made to a specification which, so far as I can see, precludes the instrument from measuring the equivalent loudness of impulsive noises with reasonable accuracy, and leads to instruments which can read 20–30 phons too low for such noises.

By an impulsive noise (a point which also arises first in the title) I mean one in which the sound consists of a single pulse with accompanying fluctuations, or of a series of such pulses (such as may occur at the exhaust of a motor-cycle engine), even though the pulses may be so rapidly repeated as to give the impression of a steady sound. Apparently Messrs. King and Churcher think it would be better to call them sounds of short duration. However, when I hear a noisy motor cycle pass me I do not think of the sound as one composed of a series of sounds of short duration—a category to which short soundings of a pure tone would belong—but as a noise composed of explosions and impulsive sounds. Moreover, it has been this " impulsiveness " of the sounds which I have had in mind in designing the meter, and in point of fact rapidly-repeated 1 000-cycle/sec. pure tones of short duration did not seem, on trial, to have the characteristics necessary for adjusting the meter to deal with the " impulsive " sounds associated with rattles and sequences of explosive noises. Consequently I do not feel that I need apologize for selecting the word " impulsive " as the most convenient single adjective, suitable for frequent use in the paper, which would graphically convey the impression of the type of sound concerned.

Reverting to the comments with which Mr. Cohen opened the discussion, I note that he considers the two most important requirements in connection with an objective noise-meter to be, first, specifiability and reproducibility, and secondly, agreement with subjective results. Mr. West considers that it is even more desirable to possess a physically specifiable noise-meter than one which has been proved to measure the equivalent loudness of sounds. If I disagree with them it is in the emphasis laid on specifiability, feeling that a specification for a meter to measure equivalent loudness of sounds should not be given if the meter is known to be seriously defective for many classes of everyday noise. If a specifiable meter is used in spite of the fact that it does not measure equivalent loudness, it should be named so that this fact is clear, and it should, as Mr. Cohen suggests, be calibrated simply in logarithmic steps. The separation of phons from decibels and other purely logarithmic steps, achieved by the International Acoustics Committee, facilitates such a procedure. As Dr. Kaye has pointed out, the International Acoustics Committee held in Paris in July, 1937, could not endorse the claims of any noise-meter which did not attempt to conform to the international phon scale of loudness, a decision which leaves possible the use and development of objective meters for measurements of equivalent loudness, within the limits of their practicability. The Committee considered a meter with a quadratic law of rectification (e.g. the American " sound-level meter " referred to by Mr. Mason) to be inadequate to deal with many classes of impulsive sounds.

Although, during the work, I had primarily in mind the object of producing an instrument which would accord with average subjective impressions sufficiently well to be worth specifying, the question of specification was in the background, and the present paper is in a form which prepares the way for a performance specification. It shows that when the meter was provided with circuits which dealt faithfully with impulsive sounds repeated at speeds of 12, 25, and 50 impulses per sec., as well as given a suitable frequency response and speed, a meter resulted which was reliable for a wide range of sounds of moderate loudness. The paper exhibits the waveform of the sounds employed, but quite possibly other sounds of similar impulsiveness would do equally well. In effect, the paper therefore suggests that, if the performance of the meter to specifiable acoustical or electrical impulses (repeated at speeds of 12, 25, and 50 per sec.) is appropriately controlled through the rectifier, and if an appropriate frequency-response and speed of indication are adopted, a useful objective noise-meter is obtained.

Mr. Fleming has recently made at the National Physical Laboratory a study of the response of the rectifier to electrical inputs consisting of a regular succession of " square-topped " impulses, the electrical impulses having different durations from about 0·1 to 10 millisec., and rates of repetition from about 10 to 100 per sec. It is hoped that this work will yield an adequate physical specification of the performance required in the rectifier of an objective noise-meter.

Apart from this development, however, the following information may be given upon the specifiability and reproducibility of the present meter. A noise meter made by a commercial firm from a general specification of components agreed to within 1 phon with the meter which is

the subject of this paper, the various laboratory noises (Nos. 2–7) being employed in the testing. Another firm, employing more modern valves and even different circuits (including a different rectifier circuit intended to have the same physical constants) and working in collaboration with the Laboratory as regards adjustment for impulsive noises, produced a meter which agreed well with the meter described in the paper.

In view of a number of comments upon details of the meter, and references to a parallel development of a leaking peak voltmeter for assessing the disturbing effect of radio-frequency radiation in wireless reception, it seems desirable to explain that the present meter has been in use for some years. As shown to the British Association in the summer of 1934 it had only elementary adjustment for impulses, but by the end of 1934 it had been adjusted on the lines described in the paper and was used, as Dr. Kaye has said, in connection with the first of the measurements of the noise of motor vehicles which were made in 1934 and onwards for the Ministry of Transport.*

The first correlations with aural measurements of loudness were made with subjective meters of various kinds, and the difficulties and ambiguities mentioned were met and surmounted. The acceptance of the "phon" by the British Standards Institution in 1936 made it desirable to repeat as many of the aural measurements as possible with the new standard technique. In the 3 years or so which have elapsed since the meter was first adjusted as described, it has been used in thousands of field measurements. In spite of inclemencies of the weather no failure occurred with the condenser microphone, and the frequent check of its sensitivity revealed no important change. Naturally if the meter were now redesigned more modern components would be used, and one firm collaborating with the Laboratory produced in 1936 a modernized form giving the same performance and using a piezoelectric microphone instead of a condenser microphone.

A simplified portable objective noise-meter designed by Mr. Fleming at the Laboratory in connection with work for the Ministry of Transport employs a piezoelectric microphone, a battery-operated amplifier, and a diode rectifier, followed by a d.c. amplifying valve operating an indicating meter. It includes a standard noise for calibration purposes.

These facts will indicate to Dr. Tucker, Dr. Hughes, and others, that the condenser microphone has functioned satisfactorily, but that piezo-electric or other microphones are not only acceptable but already in use on variants of the meter. Crystal microphones are of course less sensitive than condenser microphones, and I am a little nervous of electromagnetic or other microphones which have not a smooth frequency characteristic. I do not consider with Mr. Mason that a condenser microphone has a bad frequency characteristic, for it is smooth and easy to correct in the amplifier, but I agree that the condenser microphone is somewhat directional. However, the measurements referred to in the paper were made with the microphone facing the source of sound in open-air conditions. After all, the human head is a directional receiver and there seems no undue complication in turning the microphone of a meter to face a source of noise in the open, for one would normally turn one's head.

The time marks in Fig. 4 indicate intervals of 1/50 sec. in all cases except that of the pure tone.

Dr. Tucker draws attention to the difficulties which arise with noise-meters at levels below those for which the present meter has been studied, and which have been reserved to the future. As regards wind disturbances, I may perhaps say that these did not prove to be troublesome in the numerous open-air measurements of the noise of motor vehicles which were made in all weathers. Where wind threatened to interfere, the disturbance was avoided by placing a small screen near the microphone, e.g. the user of the noise-meter stood between the microphone and the wind. Any disturbance appeared to be due to local eddies and pressure variations caused as the wind passed the microphone itself. When wind passes human ears we normally disregard the noises which we actually hear. Nevertheless, the aerial disturbances are produced quite near to the ear drum, and the sensations of loudness to which they give rise are often considerable. For instance, in a normally "strong" wind in the Teddington district, I balanced my awareness of the wind noises heard in one ear against, in the other ear, the tone in the telephone receiver of a subjective noise-meter. The result—over 100 phons—was somewhat surprising. A microphone cannot disregard, as we do, the noisy fluctuations of pressure which arise as wind blows over it. However, Dr. Tucker's comments are noted; possibly wind disturbance could sometimes be met by suppressing the low-frequency response of the meter in cases where such response is not required for the measurements in hand, or perhaps by streamlining the microphone case.

Dr. Tucker should not assume that, since the curves of Fig. 2 are not continued in the region below 50 cycles per sec., all sensitivity ceases in the extended region. If that were the case the curves would reach the zero line and continue along it. He would be safer to extrapolate. In fact the overall acoustical sensitivities of the meter for pure tones of 20-cycle frequency were lower by 4 phons (upper scale) and 14 phons (lower scale) than the sensitivities for pure tones of 100-cycle frequency.

As regards single large impulses (such as those of maroons) to which Dr. Tucker refers, I mentioned in the paper that an attempt to obtain aural measurements of isolated impulses or impulses as infrequent as 1 per sec. led to such widely dispersed aural observations by different observers (spreads of $\pm$ 25 phons from the mean) that it was clear that the average observer experienced exceptional difficulties in judging their loudness equality with a 1 000-cycle/sec. tone. The meter gave results well within the range of aural observations, but the measurement of such slow impulses was not pursued.

In answer to Dr. Tucker and Mr. McMillan, the reference in the paper to reproducing motor-vehicle noises at "correct volume" on a loudspeaker refers to the following point. If a noise is accurately reproduced in waveform and intensity it sounds identically like the original. If, however, the intensity is increased substantially (with-

* The first Interim Report of the Committee, published in the summer of 1935, mentioned that the N.P.L. had carried out the measurements with an objective noise meter, an appendix on noise measurement mentioning adjustments to deal with intermittent sounds, whether isolated impulses or rapidly recurrent. The N.P.L. Annual Report for 1934 had mentioned what were the first adjustments of the meter to deal with impulsive sounds, and the Report for 1935 stated that attention had now been paid to intermittent noises, whether a single impulse or a repeated series, and that according to aural comparisons the instrument appeared to be at least as satisfactory as any individual hearer for moderately loud sounds.

out altering the wave-form) the low-pitched constituents of the noise come into prominence to the ear, and the sound appears to the ear to differ in quality, although physically it does not differ in anything other than intensity. Thus for the ear to hear a true reproduction of a noise of a certain quality, one must get the wave-form true and also arrange for the intensity of reproduction to be of the right order. Consequently, when an attempt was made to produce in the laboratory a noise representative of that of a motor cycle, the reproducing system was made as faithful as possible as regards wave-form reproduction, and the intensity of reproduction was adjusted so that the overall intensity (as measured by a microphone) at the listening point in the Laboratory was the same as that at the position occupied by the microphone which was picking up the original sound near the motor cycle. Analysis showed no considerable differences in content. I may point out that the object was not to measure the loudness of the motor cycle, but to get a type of noise fairly representative of motor-cycle noise for use in checking the behaviour of the objective noise-meter.

In reply to Dr. Whitehead, I think that the work of the C.I.S.P.R. had not been undertaken when my meter was first adjusted empirically for impulses, and the B.S. Specifications to which he refers had not been issued when the present paper was prepared. Moreover, I believe that the C.I.S.P.R. instrument was not for measuring sound in the air, but for electrical noise in radio sets, and this probably explains why it did not come to my attention until after my paper had left my hands. Dr. Whitehead refers to difficulties met in using the C.I.S.P.R. meter for chains of transient impulses as the speed of repetition increases. To some extent therefore the present instrument appears to be an advance on the C.I.S.P.R. circuits, for the basis of the present meter has been an attempt to get an instrument to deal appropriately with chains of transient impulses, and with the manner in which loudness changes as the frequency of repetition is varied.

Mr. Mason comments on the free-field response curves for the ear given in Fig. 2 of the paper, and based on the fairly recent but pioneer experiments of Fletcher and Munson. It will be noticed that two weighting networks were tried for the meter, as it was not desired to assume that any particular curve was the correct one. It appeared on trial that an intermediate network (corresponding to the Fletcher and Munson 75-phon ear characteristic) would have been better for noises of loudness 90 phons or so. This possibly implies that the ear characteristic varies more with frequency than Fletcher and Munson's curves indicate, a result which, I believe, is consistent with the free-field curves published by Messrs. Churcher and King.

As regards the minimum audible sound which can be measured by noise-meters, I have indicated that simulation of the ear seems likely to fail, with the present circuit adjustments, for levels below about 70 phons, and no full study has yet been made at lower levels. Consequently the question does not arise of whether the microphone or amplifier noise would first limit applicability to noises of lower intensities. There is no difficulty in making meters much more sensitive than the present one so far as intensity is concerned.

Mr. MacMillan, in studying "room noise" by an aural technique which he admits was not the direct procedure defined by the specified technique of the phon, found that the meter I have described gave results in good agreement with the aural observations, but that a meter of the American type gave results only a few phons lower, even for noises of "impulsive" type. Possibly the explanation is that a noise which consists of a succession of impulsive sounds when heard in open air conditions becomes blurred when heard in a "room," owing to the considerable overlapping and mixture of sounds due to reverberation, so that the full effect of the impulsiveness of the noise is not attained.

I have already dealt with the question of the reproduction of certain motor-cycle noise at "correct volume," explaining that my object was not to measure the loudness of the motor cycle, but to get from a loudspeaker in a laboratory a noise as nearly representative as possible of the everyday noises of a motor cycle, so that the behaviour of the noise meter to noises of this type could be examined and checked against aural measurements. In addition the impulsive noises produced artificially were selected after trial, as being, according to the judgment of hearers, at least as sharply "impulsive" as the sounds of the most "impulsive" motor-cycle exhaust heard in everyday life, and of similar pitch. There would have been no difficulty in making the laboratory noises sharper still, but motor-vehicle noise was largely in mind, because such noise leads to numerous everyday complaints.

Mr. Pawley refers to difficulties to be expected at lower levels of loudness when the matter is viewed from a certain standpoint, and mentions that further investigation is necessary to determine to what extent the sensitivity of the ear at one frequency is affected by the presence of a sound at another frequency. I do not deny the difficulties: I am aware of them. But it is not necessarily best to attempt the solution by considering a complex sound as the sum of two pure tones heard in each other's presence.

Perhaps I may express this point of view more fully. For steady complex sounds Fletcher and Munson have proposed a complicated formula by means of which the equivalent loudness of a sound may be inferred from an analysis of the sound, in conjunction with a knowledge of the thresholds of the ear for the component tones concerned. On the other hand, Steudel proposed a formula which may perhaps be said to stress the wave-form of the sound rather than its analysis, in that it related to peak impulses. Clearly any valid formula expressible in terms of analyses is but another aspect of any formula which will express loudness in terms of wave-form. In considering how to produce the present noise-meter, it seemed to me that to attack the question of an objective meter for complex noises from Fletcher and Munson's viewpoint of analysis was much more difficult than to attack it from the viewpoint of peak impulses, although the two, if equally valid, must give but different aspects of the same thing. Moreover, repeated impulsive sounds appeared likely to present a useful case, inasmuch as with them the peak aspect is obviously important and, nevertheless, the noise is analysable into an accurate harmonic series. If therefore (as appeared possible by attention to the rectifier of

the objective meter) it was possible to adjust the meter to simulate the ear in its assessment of impulsive sounds of various rates of repetition, the adjustment would make the meter correct for an important type of everyday sound for which most meters fail signally, but would also make the meter act correctly for what, viewed in another way, were a number of tones analysable into a harmonic series, and presumably assessable by Fletcher and Munson's formula. And this without considering the analysis.

Mr. Pawley asks for the exact time-constants of the circuits. As neither the charging nor discharging of the leaking peak meter are exponential, the meter has no strict time-constants. Possibly, however, it may be said, with reserve, that the time-constant for the discharge and the time-constant of the needle of the meter are each of the order of the 160 millisec. mentioned for the C.I.S.P.R. radio-interference meter, being rather lower—say 110 millisec. The rate of charge presumably depends upon the capacitance of the condenser ($0 \cdot 002\ \mu$F) in the input lead to the grid of the rectifier valve, and upon the grid-filament conductance of the valve. When the grid voltage is $\frac{1}{2}$ and $1\frac{1}{2}$ volts positive, relative to the negative end of the filament, the grid-filament currents in the valve are 2 and 40 microamperes respectively. The corresponding time-constants are less than 1 millisec. and less than $\frac{1}{10}$ millisec. respectively. When the grid voltage is rather less than $\frac{1}{2}$ volt the inferred instantaneous value of the charging time-constant is 1 millisec. At lower voltages it is much more. During the measurement of noises composed of a series of impulses the grid volts reached during the peak of the impulse depend upon the duration and frequency of the impulses, and the appropriate effective time-constant of charging depends on the nature of the noise. For some repeated impulses the constant is of the order of 1 millisec. For impulses of shorter duration, or for the same impulses repeated more slowly, the time-constant is less.

As regards the difference noticed in the behaviour of the meter to impulsive compressions and impulsive rarefactions, we did not find it possible to get proper response to impulses with a symmetrical circuit. Two diodes in push pull, and other circuits, were tried without success. Possibly they are worth further trial.

As regards the statements in the paper (Table 1) concerning the difference between impulsive compressions and rarefactions, more recent study indicates that supposed "rarefactions" (judged from the first pressure charge) sometimes give higher readings on the meter than "compressions." Probably the true criterion is not so much the initial nature of the sound impulse (i.e. compression or rarefaction) but the direction of the maximum peak in the short train of waves involved. The calibrations of the meter given in the paper refer to a condition in which the meter gave its maximum reading. In the paper it is stated that it is really necessary, when measuring "rarefactive" sounds of very impulsive character, to reverse the e.m.f. applied to the rectifier, the maximum of the two readings (if they differ) being the one which should be taken. It now appears, however, that this procedure is strictly necessary with all types of impulse, for Steudel's work indicates that the loudness of impulsive sounds is determined by the maximum impulse delivered by the disturbance in rather less than $0 \cdot 001$ sec., whether it be positive or negative.

However, although the present meter (which has no arrangements for reversal) may read low if no reversal is made it should be understood that the trouble arises only with very impulsive noises, and that even without reversal in appropriate cases the present meter would give results very much more nearly correct for such noises than meters having r.m.s. rectification, and which can read some 25–30 phons too low.

Dr. Hughes asks about distinctions between the radial and reverberant responses of the microphone. So far the meter has been used either in open air or in special high-absorbent chambers, and the question of reverberant response has not arisen. Reverberation has been avoided in order to get measurements by the standard phon technique, and in order to ensure full impulsiveness of the various sounds without complication due to overlapping of the sound and its reflections.

For some months the meter was used satisfactorily with the "free grid" as shown in the diagram. The grid was not completely free, however, because the leakage resistance of the short-circuiting key was not specially high. Experience showed, however, that the resistance of the key varied unduly with atmospheric conditions. Consequently the key was re-designed. Ceresine was used to insulate all components connected to the free grid so as to ensure a high insulation resistance, and a definite grid-leak resistance of 80 megohms was connected across the key, this being the lowest resistance consistent with correct functioning of the meter on the noises described in the paper. If the rectifying valve were changed the components of its grid circuit might need alteration also. On an occasion when a new rectifying valve was inserted, however, no changes in the associated components were necessary.

I am not clear that the loudness level of a noise is greater when its components are in harmonic relation than when they are in inharmonic relation. I believe that certain authors suggested this to be the case some time ago, on the basis of aural measurements obtained by a method, involving simultaneous listening to the noise and to the standard tone, which later work has shown to be somewhat suspect. I do not know whether any marked difference between harmonic and inharmonic sounds is claimed when the standard technique of alternate listening is employed. I would recall that the present meter was tested upon irregular noises due to motor vehicles, and upon sets of regularly repeated impulses which are necessarily analysable into tones having components in harmonic relationships. Work is now in progress on other harmonic tones chosen for their special properties in the light of Fletcher and Munson's formulae for calculating the loudness of complex sounds. The first results are very satisfactory so far as the meter is concerned.

Messrs. King and Churcher recall that they indicated in 1937 that the conventional objective noise-meter (with thermal r.m.s. or copper-oxide rectifier) would not deal correctly with some types of complex noise. Indeed, Table 10 of their paper indicates that the objective meter they used in these experiments fell short of the true reading in phons by from 6 to 19 phons when tested on impulsive and other noises in the range above 80 phons.

Presumably the inference is that one should not employ the conventional circuits which Messrs. King and Churcher envisaged.

Messrs. King and Churcher also claim to have shown that the " conventional " meter, correctly weighted, has an error usually less than 5 phons in the region above 80 phons. I do not know how this statement can be reconciled with their other contention, unless the impulsive noises are regarded as unusual in everyday life—a point of view with which I could not agree. So far as my experience goes, no meter based on r.m.s. rectification is correct to anything like 5 phons for very " impulsive " sounds. Possibly Messrs. King and Churcher attribute failures to incorrect frequency weighting, but reference to my paper will show that the considerable differences between the two weightings of my instrument (15 decibels at 50 cycles per sec.) did not have much effect on the measured loudness levels of impulsive sounds of 12–50 repetitions per sec.

Messrs. King and Churcher advance reasons why a leaking peak meter will not deal with all loudnesses of noise. If what they say is true, it suggests that for loudnesses for which a leaking peak meter is inappropriate some other form of rectifier should be tried. Readers of the paper will note that I have not dealt with any but fairly loud noises, but I would point out that one is free to vary the rectifier with loudness level, just as one is free to vary the frequency-sensitivity curve. Moreover, it should be mentioned that even at the present levels the effective time-constants of the rectifier depend somewhat upon the nature of the noise being measured.

One of the reasons advanced for lack of universality of a peak meter is that the relative phases of a noise do not affect its loudness, although they can modify the indication of a peak meter. It is well to mention, therefore, that this is not universally true. For example, Steudel found with a series of impulses that the phase relationship of the sinusoidal components was important to the ear as well as to a peak meter; again Chapper and Firestone* found the effect of phase upon the loudness of certain combined tones to be about 10 phons, and a combination of two tones in certain phase relationships to be even less loud than one of the tones alone. Moreover, the meter described in the paper is intended for fairly loud sounds, and for loud sounds Messrs. King and Churcher themselves admit that phase relationships may have significance to the ear.

Another warning given is that one should not assume that the voltage wave at the input of a peak meter is the same as that of the sound-pressure wave at the microphone. I have made no such assumptions, but have shown that, as an overall result, one can adjust a meter to be reasonably correct for pure tones and for a set of representative sounds of other classes.

Messrs. King and Churcher deprecate the giving of the spread of subjective results as being useless statistically. They apparently overlook that my Fig. 6 shows, for half of the noises, all the individual results obtained by various observers. Moreover, I wished to show—and Fig. 6 and 7 do so—that the meter gives results well within the range of individual aural judgments and very close to the mean. That, to my mind, is sufficient justification for an objective noise-meter, and justification which could not have been claimed for the r.m.s. noise-meters which I have tested. The large spread implies that there is nothing like precise agreement among individuals as to when two sounds are equally loud, and it limits the accuracy that one would need to attain in an objective noise-meter which might be accepted as a reasonably just arbiter for testing machines and other devices to a noise specification.

* *Journal of the Acoustical Society of America*, 1934, vol. 5, p. 173.

Mr. H. R. Harbottle (*in reply*): Mr. Cohen, Dr. Whitehead, and Dr. Radley, stress the need of a simple instrument suitable for measuring the equivalent disturbing current or voltage of a power system. Such an instrument would certainly reduce the calculations involved in interference problems and would be more convincing to power engineers. It is difficult to foresee how any simple instrument could give results which would even approach those obtained in practice, in view of the many considerations involved. Nevertheless, since the psophometer was first evolved, harmonic analysers have been developed and simplified. It would appear then that, assuming that the equivalent e.m.f.'s of the individual harmonics in a disturbing source do not change appreciably with load, and that any known power-circuit condition could be maintained during measurement, a harmonic analysis of the disturbing current would enable calculations of the longitudinal noise-voltage induced into a communication circuit to be made with far more accuracy than could possibly be expected from an instrument of the circuit noise-meter type.

In view of the comparatively large values recorded during measurements of the ripple e.m.f. from d.c. generators and the wave-form impurity of alternators, however, it is apparent that an instrument simpler and much less sensitive than the circuit noise-meter could be used. The frequency weighting adopted should be governed by the precise loading of the machines and the manner in which the impurities would react on communication circuits. Nevertheless, it frequently happens that a measurement of the actual interference produced is required at the same time, e.g. a measurement of the noise p.d. across the batteries at a telephone exchange or repeater station is made at the same time as the noise e.m.f. from the d.c. generators or rectifiers is determined. One instrument—the circuit noise-meter—can be adapted for both tests.

Mr. Cohen raises the question of the " B " network. He mentions the difficulty of determining a frequency/response curve which will be truly representative of all the terminations which might occur in practice. If, however, Fig. 8 can be taken as a typical example, it will be seen that the lower frequencies only are seriously affected. But the weighting network of the circuit noise-meter attenuates these frequencies considerably, and hence the frequency characteristic of this and similar terminations will not influence results to any appreciable extent. More serious effects, which would be difficult to reproduce, are the generation of unwanted frequencies due to non-linear distortion in the various components and any unbalance which may be imposed on the line under consideration. Further, as was pointed out in the paper, the weighting curve of the circuit noise-meter does not represent finality. Hence it would appear that the minor effects due to the frequency characteristics of a

" B " network should not be considered until the main weighting curve is reviewed.

Dr. Kaye is not alone in his dislike of the word " psophometer." It is understood that the term " circuit noise-meter " will replace it so far as this country is concerned.

The composition of the typical mains induction (Table 8) was obtained from a large number of analyses. As Dr. Whitehead states, the composition will change in the future owing to the increasing use of tertiary windings on 3-phase transformers and of mercury-arc rectifiers. This modification will not only include the even harmonics generated on the d.c. side of the rectifier but probably also odd harmonic modulation products which occur on the a.c. side.

For the termination given in Fig. 3, in which a subscriber's instrument is connected directly to a Stone cord circuit, the ratio of the alternating voltage across the receiver from a No. 164 telephone to that across the points

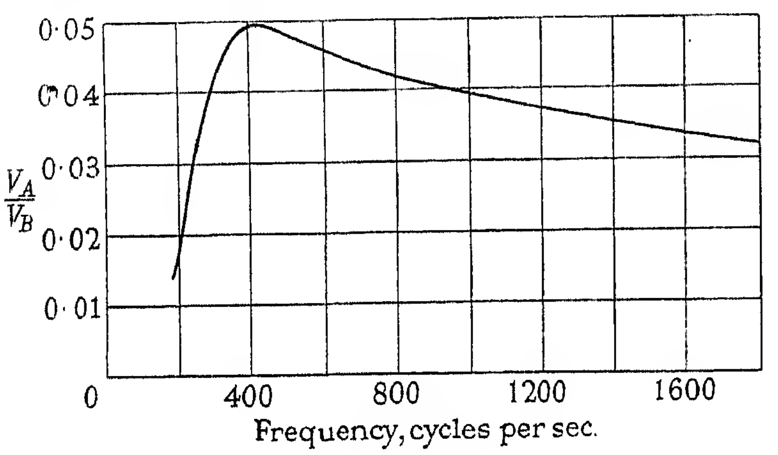


Fig. A

marked " generator " (i.e. V_A/V_B) at various frequencies is shown in Fig. A. From this it will be seen that 2 mV at 800 cycles per sec. applied across the generator terminals will produce a p.d. of 0·084 mV across the receiver. Here again the frequency characteristic is substantially flat above 400 cycles per sec., and hence no great errors will be introduced if the disturbing effect of noise across the generator terminals is measured by means of a psophometer connected directly. With regard to telephone repeater-station batteries, the ratio of the noise output from a repeater to the noise p.d. across the batteries will depend on the decoupling arrangements included in the repeater, and varies with different makes. It has, however, been found that the noise across the 24-volt " A " battery is far more disturbing than the noise across the " B " battery, since the former is used for supplying grid bias to some of the valves. Generally, the transverse noise p.d. across the output of a repeater has been found to be approximately equal to the noise voltage across the " A " battery.

The input transformer to the psophometer described in the paper was not astatically wound. Only one bobbin on the centre limb, of double E mumetal stampings, is used. No difficulty as regards screening against external magnetic fields has been experienced on account of the small physical dimensions of the transformer. The 1 : 7 transformer and the input transformers of earlier models are wound in the manner described by Dr. Whitehead.

An 800-cycle oscillator of good frequency stability has an advantage over a multi-vibrator as a calibrating source since a true calibration as distinct from a routine check is possible.

It is probable, as Mr. West states, that a psophometer which had a weighting curve very different from the one specified by the C.C.I.F. would have given results equally as representative as those obtained with the existing instrument. The earlier tests made by power and communication engineers seemed to indicate, however, that some frequency weighting was desirable, and at that time there was some justification for the curve adopted. Since this latter has been adopted as an international standard, it is desirable that no change should be made until it can be proved definitely that the existing instrument is giving results which are not truly representative. It would appear that a calibration at the peak of the weighting curve (1 050 ± 50 cycles per sec.) should be a simpler test than one at 800 cycles per sec. A frequency stability of less than 1 % can be obtained quite readily, and hence the errors suggested by Mr. West should not be introduced. It should be remembered that in early transmission measurements a frequency of 800 cycles per sec. was found to give results which were equivalent to those obtained in voice-ear tests.

With regard to the weighting curve specified for noise measurements on broadcast circuits, I cannot give an authoritative reason why the point of zero decibels is not at 800 cycles per sec. It has been suggested that the mean of the weightings for the frequencies in the band 500–5 000 cycles per sec. was taken.

On the question of overloading, continuing Mr. Fennessy's example, let us assume that a full-scale reading is obtained on the measuring instrument when 0·1 mV at 1 050 cycles per sec. is applied across the input terminals. A similar deflection would be given by 1 volt at $16\frac{2}{3}$ cycles per sec. Hence it will be apparent that, unless the majority of the weighting required for the low frequencies occurs before the first valve, there is a serious possibility of overloading. Again, the earlier the magnitude of low-frequency components is reduced the less chance there is of introducing harmonics due to components in the instrument which have non-linear characteristics.

The calibration of the psophometer is made by means of a heterodyne oscillator which is operated from batteries. The harmonic content of the oscillator used was about 1 % of the fundamental at 800 cycles per sec. No noise could be measured across the output, when the oscillator was set to zero frequency.

The channel selector for open-wire carrier telephone circuits will permit a discrimination of line noise and noise introduced in the terminal equipment of the system.

If the results plotted in Fig. 6 are compared with those given in Table 1, it will be found that the attenuation introduced by the receiver at 400 cycles per sec. as compared with its performance at 800 cycles per sec. is only 2 db., whereas the corresponding attenuation of the psophometer is 8 db. Between 800 and 2 200 cycles per sec., however, the frequency characteristic of the receiver from a No. 162 telephone is very similar to the weighting curve of the psophometer. At the level of sound which was used in the judgment tests described by Mr. Timmis, the frequency characteristic of the average human ear is substantially flat. Hence a difference between " noticeability " and psophometric voltage would be expected

for frequencies below 800 cycles per sec. From the above it will be realized that the weighting specified for the measurement of circuit noise will not necessarily be suitable for the measurement of the "noticeability" of a disturbance.

It should be pointed out that, if the time-constant of the circuit noise-meter is specified, the pointer of the indicating instrument must be brought to a definite scale position—the amount of the interference being obtained from the setting of the potentiometer devices. Difficulties will arise if the disturbance is fluctuating.

Finally, the discussion has emphasized that the amplifier-rectifier portion of the circuit noise-meter should have a substantially flat frequency-characteristic. Distorting networks can be added externally in order to cater for the various requirements which have been mentioned.

INSTITUTION NOTES

COUNCIL FOR THE YEAR 1938–1939

The scrutineers appointed at the Ordinary Meeting held on the 28th April, 1938, have reported to the President that the result of the ballot to fill the vacancies which will occur in the Council on the 30th September next is as follows:—

President: Dr. A. P. M. Fleming, C.B.E., M.Sc.

Vice-President: Prof. C. L. Fortescue, O.B.E., M.A.

Hon. Treasurer: Mr. W. McClelland, C.B., O.B.E.

Ordinary Members of Council: (Members) Dr. P. Dunsheath, O.B.E., M.A.; Prof. R. O. Kapp, B.Sc., A. P. Young, O.B.E.; (Associate Member) Dr. L. G. Brazier, B.Sc.

The Council for the year 1938–1939 will therefore be constituted as follows:—

President.

Dr. A. P. M. Fleming, C.B.E., M.Sc.

The Past-Presidents.

Vice-Presidents.

Sir Noel Ashbridge, B.Sc. (Eng.).	Prof. C. L. Fortescue, O.B.E., M.A.
J. R. Beard, M.Sc.	Johnstone Wright.

Honorary Treasurer.

W. McClelland, C.B., O.B.E.

Ordinary Members of Council.

T. E. Allibone, D.Sc., Ph.D.	E. M. Lee, B.Sc.
Col. A. S. Angwin, D.S.O., M.C.	E. Leete.
Dr. L. G. Brazier, B.Sc.	S. W. Melsom.
T. Carter.	P. L. Rivière.
P. Dunsheath, O.B.E., M.A., D.Sc.	P. J. Robinson, M.Eng.
C. E. Fairburn, M.A.	C. Rodgers, O.B.E., B.Sc., B.Eng.
F. Forrest.	C. D. Taite.
Prof. R. O. Kapp, B.Sc.	C. R. Westlake.
	G. A. Whipple, M.A.
	A. P. Young, O.B.E.

Together with the Chairman of the Meter and Instrument Section, the Chairman of the Transmission Section, the Chairman of the Wireless Section, and the Chairman and immediate Past-Chairman of each Local Centre.

THE PAGE PRIZE

The Page Prize for 1937–38 has been awarded to Mr. R. Newing for his thesis entitled "Equipment and Distribution for Large Industrial Undertakings."

LIBRARY

The Council have decided to afford facilities up to 8 p.m. on any evening during the summer (Mondays to Fridays inclusive) to members who wish to use the Institution Library after office hours. Any member desiring to be given access to the Library between 5.30 p.m. and 8 p.m. must notify the Secretary beforehand by letter, or by telephone not later than midday on the day concerned, so that the necessary arrangements can be made.

PREMIUMS

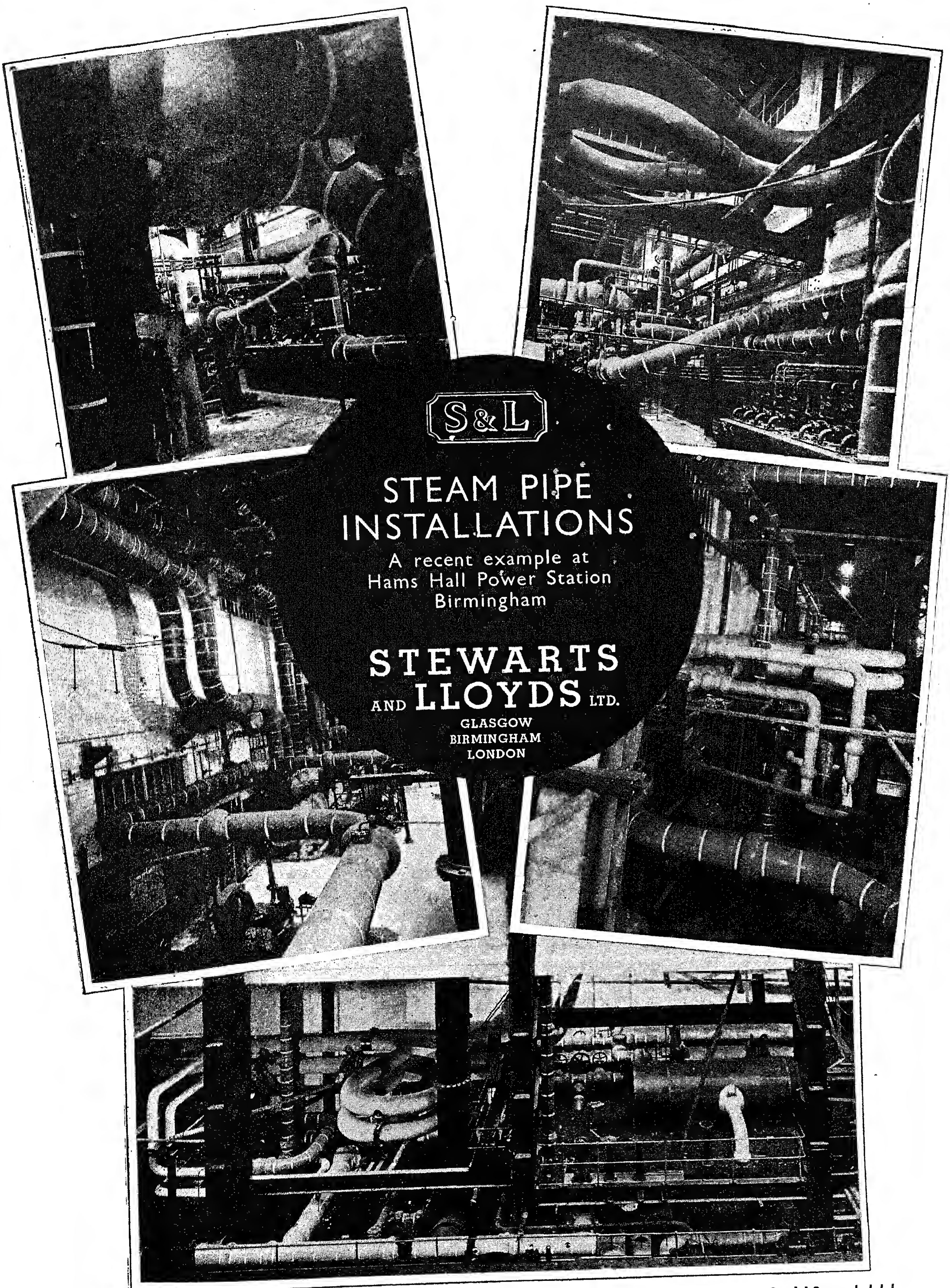
In addition to the Premiums mentioned on pages 698 and 699 of the June issue of the *Journal*, the Council have awarded the following Premiums for papers read before the Students' Sections during the Session 1937–38:—

Premiums of the value of £10 each:

Author	*Title of Paper*	*Where read*
J. E. Houldin, B.Eng.	"Television Transmission"	Liverpool
J. R. Hughes	"The Commercial and Laboratory Testing of Telephone Instruments"	London
J. M. Meek, M.Eng.	"The Electric Spark"	Manchester
G. H. Rawcliffe, B.A.	"The Limits of Theory in Electrical Machine Design"	Liverpool

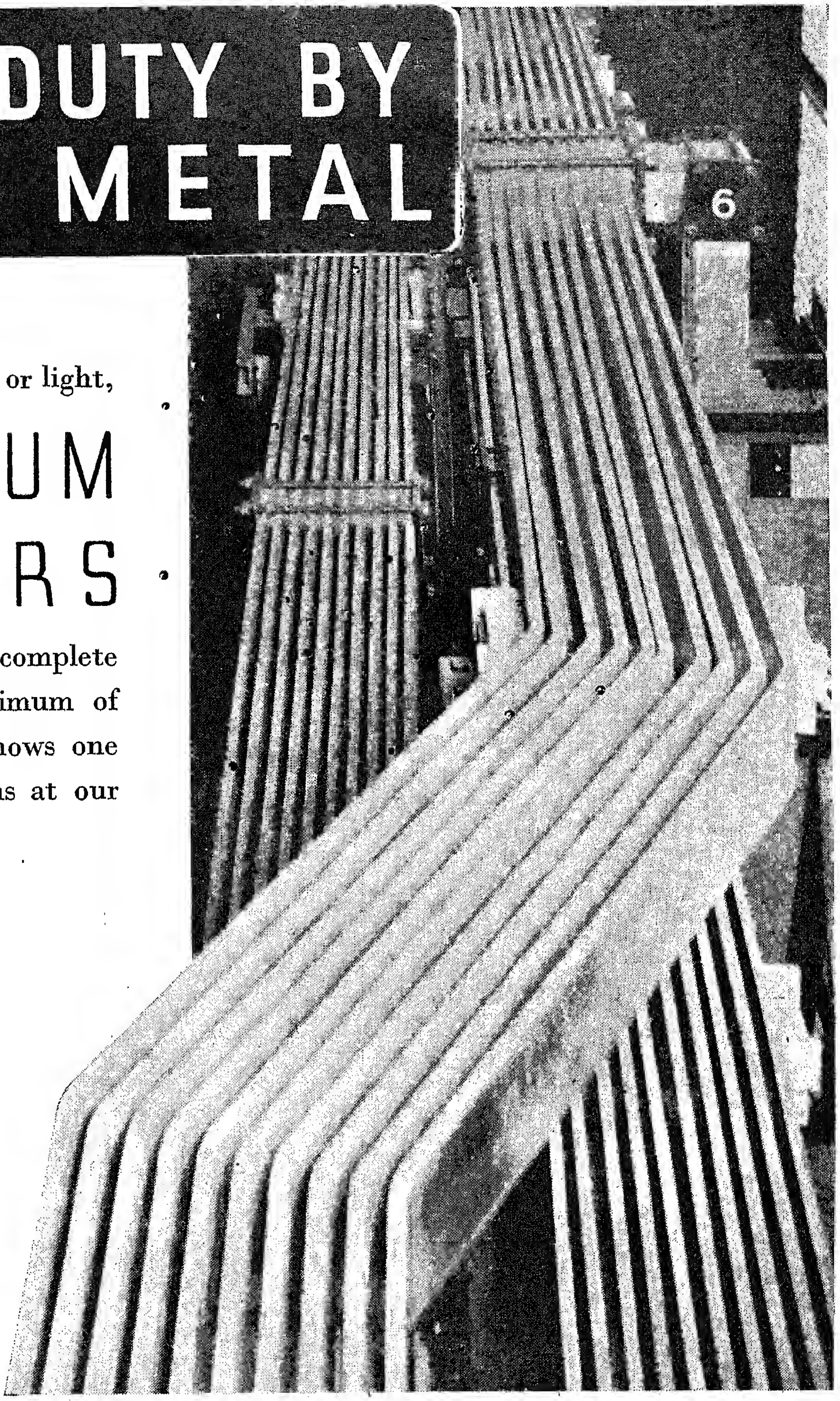
Premiums of the value of £5 each:

Author	*Title of Paper*	*Where read*
J. Bertram, B.Sc.	"The Planning of Street Lighting"	Birmingham
R. J. Franklin, B.A.	"Some Aspects of Fusible Cut-outs"	Birmingham
G. G. Isaacs, B.Sc.	"Modern Electric Discharge Lamps"	London
C. H. W. Lackey	"The Protection of A.C. Networks and Plant"	Newcastle
T. M. Lott	"Short-wave Wireless Transmission and the Amateur"	Liverpool
P. d'E. Stowell, B.Sc.	"Engineering Applications of the Laws of Chance"	Edinburgh
J. E. Woolaston	"Mercury-Arc Convertors and their Control"	Loughborough
J. L. Wooldridge, B.Sc.	"Electricity in Railway Signalling"	Edinburgh & Glasgow



We are exhibiting at the Empire Exhibition, Glasgow, Stands Nos. E. 98, 99, 110 and 111

HEAVY DUTY BY LIGHT METAL



Whether for heavy duty or light,

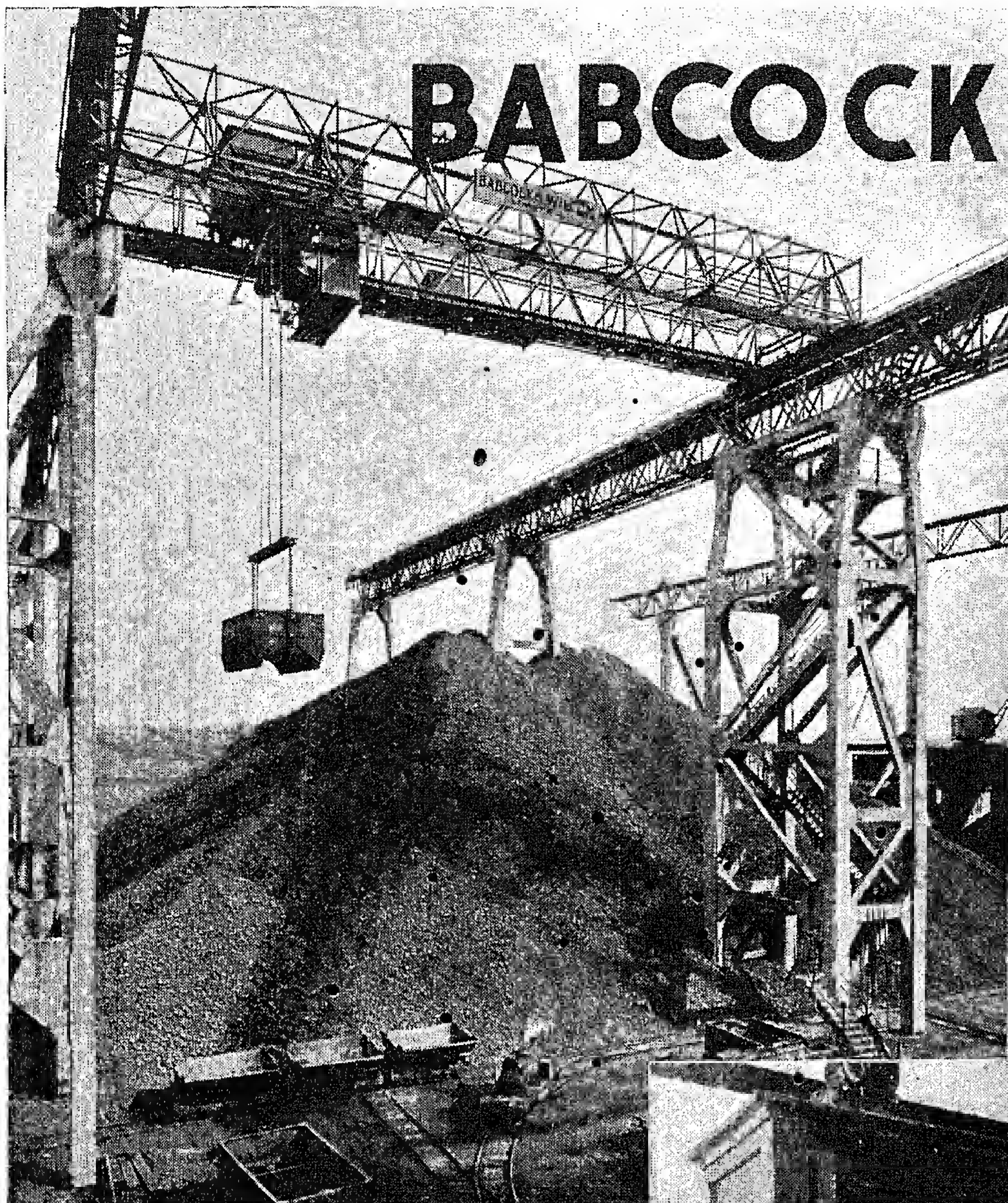
ALUMINIUM BUSBARS

perform their duty with complete reliability and the minimum of cost. The illustration shows one of the main busbar runs at our Lochaber works.

EMPIRE EXHIBITION
SCOTLAND 1938
PALACE OF ENGINEERING
STANDS
E.38 & E.128

THE British Aluminium CO. LTD

HEAD OFFICE: ADELAIDE HOUSE, LONDON, E.C.4
Telephone: Mansion House 5561. Telegrams: "Cryolite, Bilgate, London."



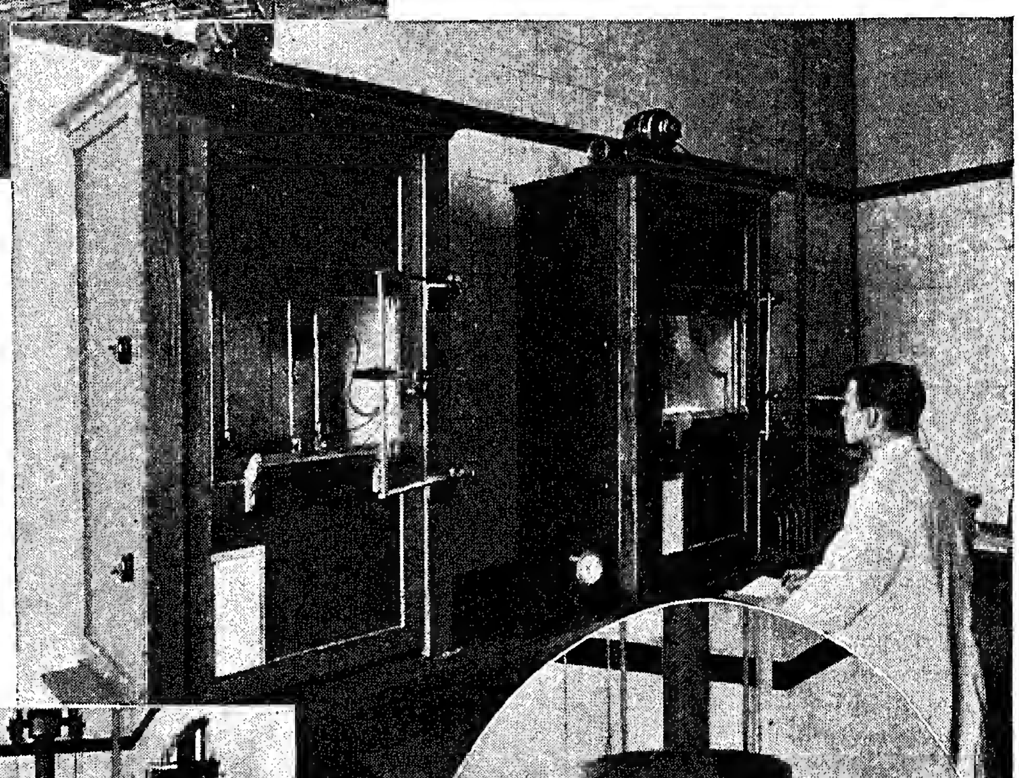
BABCOCK RESEARCH

(RESEARCH ADVERTISEMENT NO. 2.)

THE maintenance of a high standard of combustion efficiency and the design of steam generating plants capable of long periods of continuous service are largely dependent on the accurate determination of the fundamental properties of a wide variety of fuels from all parts of the World.

The FUEL SECTION of the BABCOCK RESEARCH LABORATORIES is elaborately equipped for this work and includes special apparatus which has been developed and built by the Research Department.

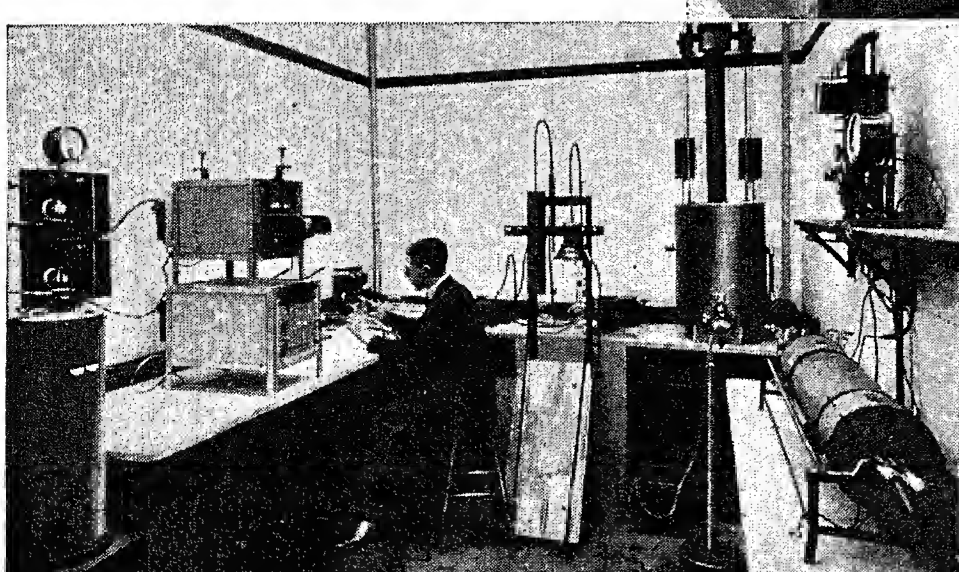
These investigations cover a wide field and include the determination of moisture contents, carbon and hydrogen contents, pulverising qualities of fuels, and the determination of volatile matter and ash content. Special attention is paid to the physical characteristics of ash.

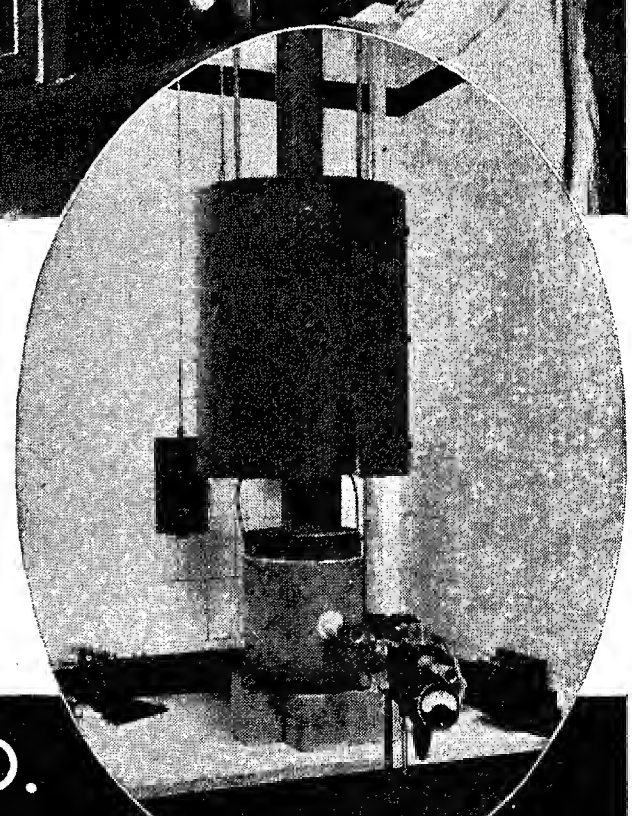


The illustration on the right shows two High Pressure Oxygen Bomb Calorimeters specially arranged for external operation and observation.

The remaining illustrations show the Furnace Room in which is installed apparatus for the determination of carbon and hydrogen content, also automatically controlled electric furnaces, and a close-up view of the Ash Fusion Furnace for temperatures up to 1600°C.

A copy of reprint No. 1179, from a technical paper article: "Reduction of Coal Samples for Analysis", will be sent on application.





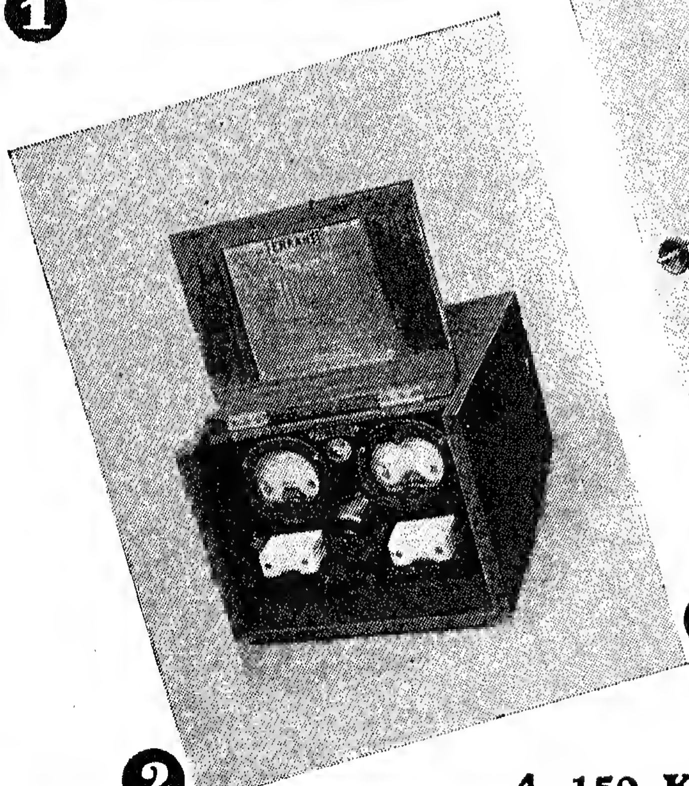
BABCOCK & WILCOX LTD.

BABCOCK HOUSE, 34 FARRINGDON STREET, LONDON, E.C.4

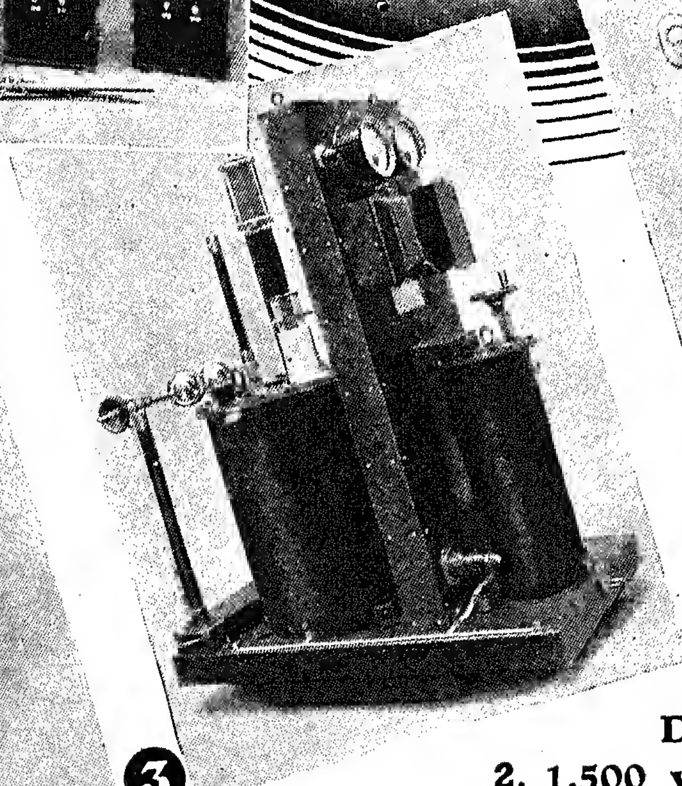
"For Securing the Safety of the Public and for ensuring a proper and sufficient supply of Electrical Energy"

—ELECTRICAL SUPPLY REGULATIONS 1937

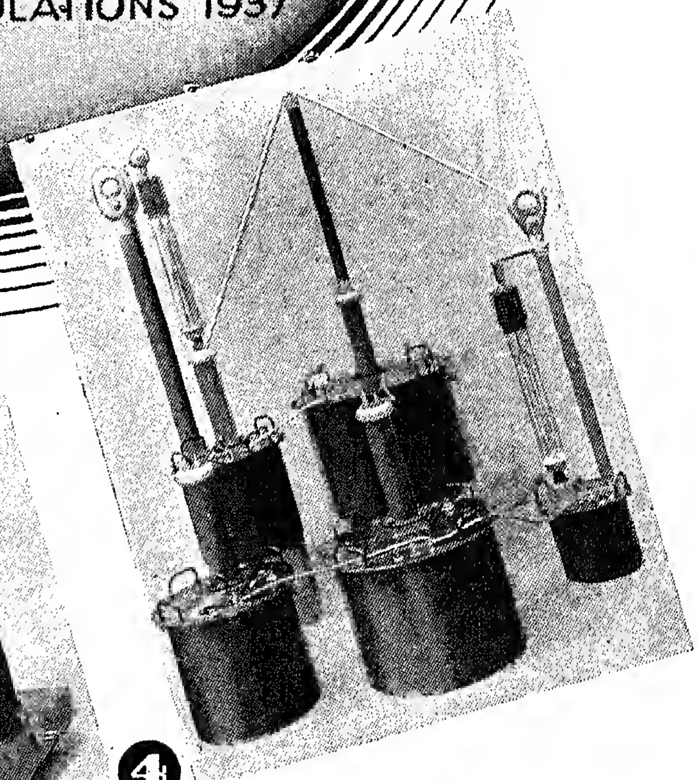
1



2



3



4

1. 40 KV. (mid point earthed) D.C. Set for testing H.T. Cables.

2. 1,500 volt D.C. Set for testing low and medium voltage cables.

3. 10 K.V.A. 80 K.V. A.C. Testing Set for testing busbars and apparatus.

4. 150 K.V. (one end earthed) D.C. Set for testing H.T. Cables.

F.T.40.

FERRANTI H.T. TESTING SETS

FERRANTI LTD., HOLLINWOOD, LANCS. *London Office*: Bush House, Aldwych, W.C. 2.

LIST OF ADVERTISERS IN THIS ISSUE

I.E.E. PUBLICATIONS

The Journal.
Published monthly, and circulated free of charge to members of all classes. Single Numbers: members of all classes, 5s. 3d.; non-members, 10s. 6d.

Ten-Year Index to the Journal.
To Vols. 1–10 (1872–82), 2s. 6d.; 11–20 (1882–91), 2s. 6d.; 21–30 (1891–1901), 2s. 6d.; 31–47 (1901–1911), 2s. 6d.; 48–59 (1912–21), 2s. 6d.; 60–69 (1922–31), 10s. 6d.

Proceedings of the Wireless Section.
Published two or three times yearly, and circulated free of charge to members of the Wireless Section. Additional Numbers: members of all classes, 2s. 6d.; non-members, 5s.

Students' Quarterly Journal.
Published in March, June, September, and December, and circulated free of charge to Students, and Graduates under the age of 28. Single Numbers: members of all classes, 1s. 6d.; non-members, 2s. 6d. Annual Subscription: members of all classes other than Students, and Graduates under the age of 28, 6s.; non-members, 10s.

Science Abstracts (Section A, Physics; Section B, Electrical Engineering).
Published monthly. Consists of full abstracts from the leading Scientific and Technical Journals of the whole world, thus presenting in a form convenient for immediate reference a complete and concise record of the progress of Electrical Engineering and Physical Science. Single Numbers: members of all classes, 1s. 9d.; non-members, 3s. 6d. Annual Subscription: members of all classes other than Students and Graduates under the age of 28, one Section 12s. 6d., both Sections 20s.; Students, and Graduates under the age of 28, one Section 5s., both Sections 7s. 6d.; non-members, one Section 35s., both Sections 60s.

History and Objects of the Institution.
Supplied free of charge to both members and non-members.

Catalogue of the Lending Library.
Revised 1936. Supplied free of charge to members.

Regulations for the Electrical Equipment of Buildings (formerly I.E.E. Wiring Rules).
Tenth edition, September 1934. Bound in cloth covers, 1s. 6d. (postage 3d.). Bound in paper covers, 1s. (postage 2d.).

Regulations for the Electrical Equipment of Ships.
Second edition, June 1926. Bound in cloth covers, 3s. 6d. (postage 2d.). Bound in American cloth covers, 2s. 6d. (postage 2d.).

Model Forms of General Conditions.
Form A. For Home Contracts (with erection). Revised April 1929. 2s. (postage 2d.).
Form B1. For Export (delivery f.o.b.). Revised December 1928. 1s.
Form B2. For Export (including complete erection or supervision of erection). Revised December 1928. 1s.
Form C. For the Sale of Goods other than Cables (Home, without erection). Issued April 1924. 6d.
Form D. For the Sale of Cables (Home, without erection). Issued April 1924. 6d.

Papers set at the Graduateship Examination.
Price 1s. per set.

The above publications are post free except where otherwise stated. They can be obtained from the Secretary of The Institution of Electrical Engineers, Savoy Place, Victoria Embankment, London, W.C.2, or from Messrs. E. and F. N. Spon, Ltd., 57 Haymarket, London, S.W.1.

NORTH-WESTERN CENTRE.

Chairman.—J. W. THOMAS, LL.B., B.Sc.Tech.
Hon. Secretary.—L. H. A. CARR, M.Sc.Tech., "Oakleigh," Cambridge Road, Hale, Altrincham, Cheshire.

SCOTTISH CENTRE.

Chairman.—MAJOR H. BELL, O.B.E., T.D.
Hon. Secretary.—R. B. MITCHELL, 154, West George Street, Glasgow, C.2.
Hon. Assist. Secretary.—H. V. HENNIKER, 172, Craigleith Road, Edinburgh.

Dundee Sub-Centre.

Chairman.—A. GRANT.
Hon. Secretary.—P. PHILIP, c/o Electricity Supply Dept., Dudhope Crescent Road, Dundee.

SOUTH MIDLAND CENTRE.

Chairman.—H. HOOPER.
Hon. Secretary.—R. H. RAWLL, 65, New Street, Birmingham.

East Midland Sub-Centre.

Chairman.—D. H. PARRY, B.Sc.
Hon. Secretary.—J. F. DRIVER, Brighton House, Herrick Road, Loughborough.

WESTERN CENTRE.

Chairman.—H. G. WEAVER.
Hon. Secretary.—H. R. BEASANT, 77, Old Market Street, Bristol, 2.

Devon and Cornwall Sub-Centre.

Chairman.—H. MIDGLEY, M.Sc.
Hon. Secretary.—W. A. GALLON, B.Sc., c/o City Electrical Engineer's Office, Armada Street, Plymouth.

West Wales (Swansea) Sub-Centre.

Chairman.—E. F. COPE.
Hon. Secretary.—R. RICHARDS, 78, Glanbrydan Avenue, Swansea.

Hampshire Sub-Centre (directly under the Council).

Chairman.—W. F. RAWLINSON, D.Sc.
Hon. Secretary.—A. G. HISCOCK, c/o City of Portsmouth Electricity Undertaking, 111, High Street, Portsmouth, Hants.

Northern Ireland Sub-Centre (directly under the Council).

Chairman.—F. H. WHYSALL.
Hon. Secretary.—J. MCCANDLESS, M.Sc., Burn Brae, Strangford Avenue, Belfast.

INFORMAL MEETINGS.

Chairman of Committee.—J. F. SHIPLEY.

METER AND INSTRUMENT SECTION.

Chairman.—H. COBDEN TURNER.

TRANSMISSION SECTION.

Chairman.—J. L. EVE.

WIRELESS SECTION.

Chairman.—T. WADSWORTH, M.Sc.

OVERSEAS COMMITTEES.

AUSTRALIA.

New South Wales.

Chairman.—V. L. MOLLOY.
Hon. Secretary.—W. J. MCCALLION, M.C., c/o Electrical Engineers Branch, Dept. of Public Works, Sydney.

Queensland.

Chairman and Hon. Secretary.—J. S. JUST, c/o P.O. Box 1067N, G.P.O., Brisbane.

South Australia.

Chairman and Hon. Secretary.—F. W. H. WHEADON, Kelvin Building, North Terrace, Adelaide.

Victoria and Tasmania.

Chairman and Hon. Secretary.—H. R. HARPER, 22–32, William Street, Melbourne.

Western Australia.

Chairman.—J. R. W. GARDAM.
Hon. Secretary.—A. E. LAMBERT, B.E., 35, The Esplanade, South Perth.

CEYLON.

Chairman.—MAJOR C. H. BRAZEL, M.C.
Hon. Secretary.—D. P. BENNETT, c/o Messrs. Walker Sons & Co., Ltd., Colombo.

INDIA.

Bombay.

Chairman.—R. G. HIGHAM.
Hon. Secretary.—A. L. GUILFORD, B.Sc.Tech., Electric House, Post Fort, Bombay.

Calcutta

Chairman.—F. T. Hom
Hon. Secretary.—D. H
Supply Corporati

Chairman.—PROF. 1
Hon. Secretary.—J.
Industries (Indi

Chairman and Hon. S
tricity Dept., P

Chairman.—F.
Hon. Secretary.
ton, C.1.

Chairman and H
Johannesbu

LOCAL HONORARY SECRETARIES A

ARGENTINE: R. G. PARROTT, Tucuman 117, Buenos Aires.
CANADA: F. A. GABY, D.Sc., Vice-President, The British American Oil Co., Ltd., 14th Floor, Royal Bank Building, Toronto, Ontario.
CAPE, NATAL, AND RHODESIA: G. H. SWINGLER, City Electrical Engineer, Corporation Electricity Dept., Cape Town.
FRANCE: P. M. J. AILLERET, 20, Rue Hamelin, Paris (16e).
HOLLAND: A. E. R. COLLETTE, Heemskerckstraat, 30, The Hague.
INDIA: K. G. SILLAR, c/o Calcutta Electric Supply Corporation, Post Box 304, Calcutta.
ITALY: L. EMANUELI, Via Fabio Filzi, 21, Milan.
JAPAN: I. NAKAHARA, No. 40, Ichigaya Tanimachi, Ushigomeku, Tokio.
NEW SOUTH W
Engineer, I
Sydney.
NEW ZEALAN
ton, C.1.
QUEENSLAND:
Brisbane.
SOUTH AUSTR
North Terr
TRANSVAAL:
UNITED STAT
J. G. Whit
New York,
VICTORIA ANI
Street, Mel
WESTERN AU
The Unive

STUDENTS' SECTIONS.

LONDON.

Chairman.—P. H. PETTIFOR.
Hon. Secretary.—A. H. YOUNG, "Park View," Alton Road, Roehampton, S.W.15.

NORTH-WESTERN.

Chairman.—R. NOONAN.
Hon. Secretary.—R. M. A. SMITH, Meter Engineering Dept., Metropolitan-Vickers Electrical Co., Ltd., Trafford Park, Manchester, 17.

SCOTTISH.

Chairman.—J. BROWN.
Hon. Secretary.—G. H. WIRE, c/o Mrs. Cormie, 8, Townhead Terrace, Paisley.

NORTH-EASTERN.

Chairman.—F. M. BRUCE.
Hon. Secretary.—J. A. STANFIELD, 44, Shipley Avenue, Milvain, Newcastle-on-Tyne.

MERSEY AND NORTH WALES (LIVERPOOL).

Chairman.—T. E. A. VERITY, B.Sc.Tech.
Hon. Secretary.—W. H. PENLEY, B.Eng., Laboratories of Applied Electricity, The University, Liverpool, 3.

SOUTH MIDLAND.

Chairman.—J. E. WOOLLASTON.
Hon. Secretary.—B. S. COPSON, 88, Reservoir Road, Olton, Birmingham.

NORTH MIDLAND.

Chairman.—A. H. MARSH.
Hon. Secretary.—G. H. WARNE, 6, Parkfield Road, Shipley, Yorkshire.

SHEFFIELD.

Chairman.—H. A. WAINWRIGHT, B.Eng.
Hon. Secretary.—C. C. HALL, 4, Meadow Head Avenue, Woodseats, Sheffield, 8.

BRISTOL.

Chairman.—W. H. SMALL.
Hon. Secretary.—J. W. DORRINGTON, 20, Trelawney Road, Cotham, Bristol, 6.

THE I.E.E. BENEVOLENT FUND.

There are many members and former members of The Institution who are finding life difficult. Please help them by sending an annual subscription or a donation to the I.E.E. Benevolent Fund.

The object of the Fund is: "To afford assistance to necessitous members and former members (of any class) of The Institution of Electrical Engineers who have paid their subscription for at least five years consecutively or compounded therefor, and to the dependants of such members or former members."

Subscriptions and Donations should be addressed to
THE HONORARY SECRETARY, THE BENEVOLENT FUND,
THE INSTITUTION OF ELECTRICAL ENGINEERS,
SAVOY PLACE, W.C.2.

LOCAL HON. TREASURERS OF THE FUND.

Irish Centre: T. J. MONAGHAN. *North-Eastern Centre:* N. CRESSWELL. *North Midland Centre:* R. M. LONGMAN. *Sheffield Sub-Centre:* W. E. BURNAND. *North-Western Centre:* T. E. HERBERT. *Mersey and North Wales (Liverpool) Centre:* A. C. LIVESEY. *Scottish Centre: (Glasgow)* A. LINDSAY; *(Edinburgh)* D. S. MUNRO. *Dundee Sub-Centre:* P. PHILIP. *South Midland Centre:* W. Y. ANDERSON. *Western Centre: (Bristol)* E. P. KNILL; *(Cardiff)* J. W. ELLIOTT. *Hampshire Sub-Centre:* W. P. CONLY, M.Sc.

PRINTED BY UNWIN BROTHERS LIMITED, LONDON AND WOKING